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Review

Virtual Reality Applications in Medicine During the COVID-19 Pandemic: Systematic Review

Federica Pallavicini[1,2], PhD; Alessandro Pepe[1,2], PhD; Massimo Clerici[3], PhD; Fabrizia Mantovani[1,2], PhD

[1]Department of Human Sciences for Education, Università degli Studi di Milano-Bicocca, Milano, Italy

[2]Gamers VR Lab, Università degli Studi di Milano-Bicocca, Milano, Italy

[3]Department of Medicine and Surgery, Università degli Studi di Milano-Bicocca, Monza, Italy

Corresponding Author:
Federica Pallavicini, PhD
Department of Human Sciences for Education
Università degli Studi di Milano-Bicocca
Piazza dell'Ateneo Nuovo 1
Milano, 20126
Italy
Phone: 39 0264484931
Email: federica.pallavicini@unimib.it

Abstract

Background: Virtual reality can play an important role during the COVID-19 pandemic in the health care sector. This technology has the potential to supplement the traditional in-hospital medical training and treatment, and may increase access to training and therapies in various health care settings.

Objective: This systematic review aimed to describe the literature on health care–targeted virtual reality applications during the COVID-19 crisis.

Methods: We conducted a systematic search of the literature on the PsycINFO, Web of Science, and MEDLINE databases, according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis guidelines. The search string was as follows: "[(virtual reality)] AND [(COVID-19) OR (coronavirus) OR (SARS-CoV-2) OR (healthcare)]." Papers published in English after December 2019 in peer-reviewed journals were selected and subjected to the inclusion and exclusion criteria. We used the Mixed Methods Appraisal Tool to assess the quality of studies and the risk of bias.

Results: Thirty-nine studies met the inclusion criteria. Seventeen studies showed the usefulness of virtual reality during the COVID-19 crisis for reducing stress, anxiety, depression, and pain, and promoting physical activity. Twenty-two studies revealed that virtual reality was a helpful learning and training tool during the COVID-19 crisis in several areas, including emergency medicine, nursing, and pediatrics. This technology was also used as an educational tool for increasing public understanding of the COVID-19 pandemic. Different levels of immersion (ie, immersive and desktop virtual reality), types of head-mounted displays (ie, PC-based, mobile, and standalone), and content (ie, 360° videos and photos, virtual environments, virtual reality video games, and embodied virtual agents) have been successfully used. Virtual reality was helpful in both face-to-face and remote trials.

Conclusions: Virtual reality has been applied frequently in medicine during the COVID-19 pandemic, with positive effects for treating several health conditions and for medical education and training. Some barriers need to be overcome for the broader adoption of virtual reality in the health care panorama.

Trial Registration: International Platform of Registered Systematic Review and Meta-analysis Protocols (INPLASY) INPLASY202190108; https://inplasy.com/inplasy-2021-9-0108/

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KEYWORDS

virtual reality; medicine; mental health; physical health; education; training; COVID-19

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Introduction

Background

On March 11, 2020, the World Health Organization declared the spread of the novel coronavirus (COVID-19) a global pandemic [1]. As a primary measure to control the spread of the virus, many governments worldwide recommended staying at home and practicing social distancing, dramatically affecting people's daily lives [2-4]. Health care represents one of the sectors most affected by the adverse effects of the COVID-19 pandemic [5]. Prolonged rules of social distancing and stay-at-home directions caused relevant difficulties in carrying out several in-hospital clinical activities [6,7], and the sudden interruption of medical education and training programs [8-10].

In such times of isolation and limited resources due to the COVID-19 crisis, information and communication technologies (ICTs) have empowered medical institutions to meet mental health and learning needs with scalable solutions [11,12]. Virtual reality (VR) represents an ICT development with the potential to revolutionize clinical support and education [13-17].

By definition, VR is a set of technologies, including head-mounted displays (HMDs), computers, and mobile devices, that can immerse users in a 3D environment to different degrees [18-21], from a simple presentation on a 2D display screen system (ie, desktop VR) up to highly immersive systems (ie, immersive VR) that use HMDs.

VR in the last decade has become a game changer for the health care sector in more than one way [22-25], representing a helpful instrument both for the treatment of several health conditions and for medical education and training [22,25-28]. This technology has been successfully applied to a wide range of mental disorders [29,30], including anxiety [31-33] and depression [34]. Furthermore, VR is being used in physical rehabilitation for improving motor function, fitness, movement quality, and mobility [35,36], and it has also been adopted as an enjoyable method for managing pain [37-40]. Regarding education and training, VR was greatly appreciated by medical and nursing students [41-43], and proved to play a crucial role in improving medical knowledge [44-46] and fostering surgical skills [44,46,47].

Therefore, during the COVID-19 crisis, VR has the potential to supplement the traditional in-hospital medical training and treatment [48], and may increase access to training and therapies in various health care settings [49,50].

Research Question

Since, to the best of our knowledge, no previous work has investigated the use of health care–targeted applications of VR during the COVID-19 crisis, this systematic review aimed to describe the literature on this topic.

Methods

Databases Searched

A systematic search of the literature was performed on March 3, 2022, by 2 of the authors (FP and AP) following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [51]. The review was preregistered (September 29, 2021) in the International Platform of Registered Systematic Review and Meta-analysis Protocols (INPLASY; INPLASY202190108). The search databases were PsycINFO, Web of Science, and MEDLINE.

Inclusion Criteria

Two authors (FP and AP) established clear inclusion criteria to determine papers' eligibility for inclusion in the review. Only studies meeting the following criteria were considered eligible for inclusion: (1) type of participant: all human participants (clinical and nonclinical population); (2) intervention: VR; (3) comparators: usual intervention, non-VR group, or none; (4) outcomes: focused on health care–targeted applications of VR during the COVID-19 pandemic; and (5) study design: randomized controlled trial (RCT), quantitative nonrandomized study (eg, nonrandomized controlled trial and case-control study), quantitative descriptive study (eg, survey, case series, and case report), or mixed methods study.

Papers published in English between December 2019 and March 2022 in peer-reviewed journals were selected and subjected to the inclusion criteria outlined above.

Exclusion Criteria

Studies were excluded if they (1) did not use VR; (2) did not focus on the applications of VR for the treatment of health conditions, or for medical education and training during the COVID-19 pandemic; (3) did not describe research conducted after the outbreak of the COVID-19 crisis; (4) did not specify the period when the study was conducted; (5) did not include outcome measures or did not include complete results; (6) did use only qualitative data; and (7) were letter to the editor articles, commentaries, or reviews.

Search Terms and Selection of Papers for Inclusion

The search string was as follows: "[(virtual reality)] AND [(COVID-19) OR (coronavirus) OR (SARS-CoV-2) OR (healthcare)]."

Initially, 2 authors (FP and AP) checked the titles and abstracts of identified articles to determine their eligibility. Subsequently, they independently reviewed the full text of potentially eligible papers. A consensus between the authors (FP and AP) resolved disagreements. When papers provided insufficient data for inclusion in the analysis, the corresponding authors were contacted to provide additional data. Five additional articles emerged via hand-searching and reviewing the reference lists of relevant papers.

Study Quality and Risk of Bias Assessment

We used the Mixed Methods Appraisal Tool (MMAT) [52] to assess the methodological quality of the studies included and the risk of bias. Studies could be awarded a score of 0, 25, 50, 75, or 100 (with 100 being the highest quality). The MMAT has high reliability and efficiency as a quality assessment protocol and can concomitantly appraise methodological quality across various empirical research [53]. Two authors (FP and AP) independently assessed the studies' quality. Interrater

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reliability was calculated with Cohen kappa [54], using the software package SPSS (IBM Corp).

Data Extraction

Two authors (FP and AP) independently extracted the following data.

Study Characteristics

The study characteristics included (1) the *study outcomes* (treatment, education, and training); (2) the *study design* used (RCT, quantitative nonrandomized study, quantitative descriptive study, or mixed methods study); (3) the *populations* included in the study (sample size, profession or health condition, gender, mean age or age range, and nationality); and (4) the *measures used for the assessment of outcomes* (eg, self-report questionnaires, semistructured interviews, and users' session data). An indication of the mean age or age range identified studies conducted on children (ie, under 12 years old), adolescents (12-18 years old), young adults (18-35 years old), middle-aged adults (36-55 years old), and older adults (over 55 years old). The division in these age ranges followed previous studies [55-57]. Regarding the study outcomes, we divided the selected papers into 2 main domain-specific categories related to VR applications in health care: (1) treatment, and (2) education and training.

VR Characteristics

The VR characteristics included (1) the *level of immersion* (high, medium, or low); (2) in the case of immersive VR, the specific *type of HMD* (ie, PC-based, console-based, mobile, or standalone system); (3) the *content* (virtual environments, 360° photos and videos, embodied virtual agents, VR video games, social VR platforms, or hybrid); (4) the *site of use* (face-to-face or remotely), the *user mode* (single user or multiuser); and (5) the *time of use* (the total amount of sessions and VR duration of use). The level of immersion, defined as a quantifiable feature of a technology that includes the extent to which it is possible to immerse oneself in the virtual world through interfaces [58], was considered because, based on it, it is possible to distinguish VR in different categories [18-21] (Table 1). Second, in the case of studies where an HMD was used, the model was specified to describe its specific type based on its implemented technologies (Table 1). Third, since there are different types of experiences in VR, information on the content was included (Table 1). Fourth, the site of use was considered since it represents crucial information concerning how VR can be offered. Fifth, information on user mode was included since VR content can be single user (ie, usable by a single user) or multiuser (ie, 2 or more users can share the same VR experience and communicate or interact with it). Finally, in the studies that indicated the time of VR use, this information was included, offering valuable insights about how and how long to use this technology to treat mental and physical health conditions, and in medical education and training.

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Table 1. Classification of the level of immersion in virtual reality (VR) systems [18-21], the types of head-mounted displays, and the VR content.

Variable	Definition	Hardware/examples
Immersion		
High (immersive VR[a])	The user is immersed within a 3D content.	HMDs[b]
Medium (semi-immersive VR)	Rooms within which computer-generated environments are projected onto the walls.	C-Automatic Virtual Environment (CAVE)
Low (desktop VR)	Computer-generated environments made in 3D but which are shown on 2D displays.	PC, television, mobile phone, or tablet screen
Types of HMDs		
PC-based	Requires a connection between an HMD and a computer with advanced computational and graphics capabilities.	Oculus Rift S and HTC Vive
Console-based	Needs a connection between an HMD and a specific game console.	PlayStation VR
Mobile	Involves the integration of VR systems on mobile devices thanks to specific HMDs.	Samsung Gear VR and low-cost HMDs compatible with mobile phones, such as Google Cardboard
Standalone (all-in-one)	They do not need other technologies to work.	Meta Quest II, HTC Vive Focus, and Pico Interactive Neo
Content		
Virtual environments	Simulation on a computer of 3D environments, which can be explored in real-time and in which the user can interact with objects contained within it [59]. They are created through specific software such as Unreal or Unity.	N/A[c]
360° videos and photos	Images or videos of real or digital environments presented in a spherical version. They provide a spherical view with multiple viewing angles and perspectives. The contents are omnidirectional and can either be computer generated or captured from the real world [60].	YouTube VR and Google Earth VR
Embodied virtual agents	Graphical representations of the individuals controlled by the computer itself using an artificial intelligence program [61].	N/A
VR video games	Video games played through HMDs in which the player can interact with virtual content not only through a joypad or a keyboard, but also using head rotation, eye movements, or specially designed controllers that respond to the position and movements of the player in a defined space [62]. They include the following: - Commercial off-the-shelf video games that are “games that one can purchase on the high street” [63], or rather purchasable in online or physical stores - Custom-made games, often defined in the literature as “serious games” [64], that are games created ad hoc by researchers to educate, train, or change behavior	Beat Saber, Half-Life: Alyx, Superhot VR, and Fruit Ninja VR
Social VR platforms	3D virtual spaces where multiple geographically remote users can interact with one another through VR HMDs [65,66]. At present, several online VR applications with a social component exist.	AltspaceVR, Horizon Worlds, VRChat, and VRzone

[a]VR: virtual reality.

[b]HMD: head-mounted display.

[c]N/A: not applicable.

Results

Overview

The search strategy retrieved 2503 records published after December 2019. A total of 1687 studies remained after deduplication and language examination, and 905 records were excluded after the first screening, and title and abstract analysis. Full-text copies of the 782 remaining studies were obtained and subjected to further evaluation. After reading the full-text copies, 743 studies were excluded based on our exclusion criteria, resulting in 39 studies being included in our systematic review (Figure 1).

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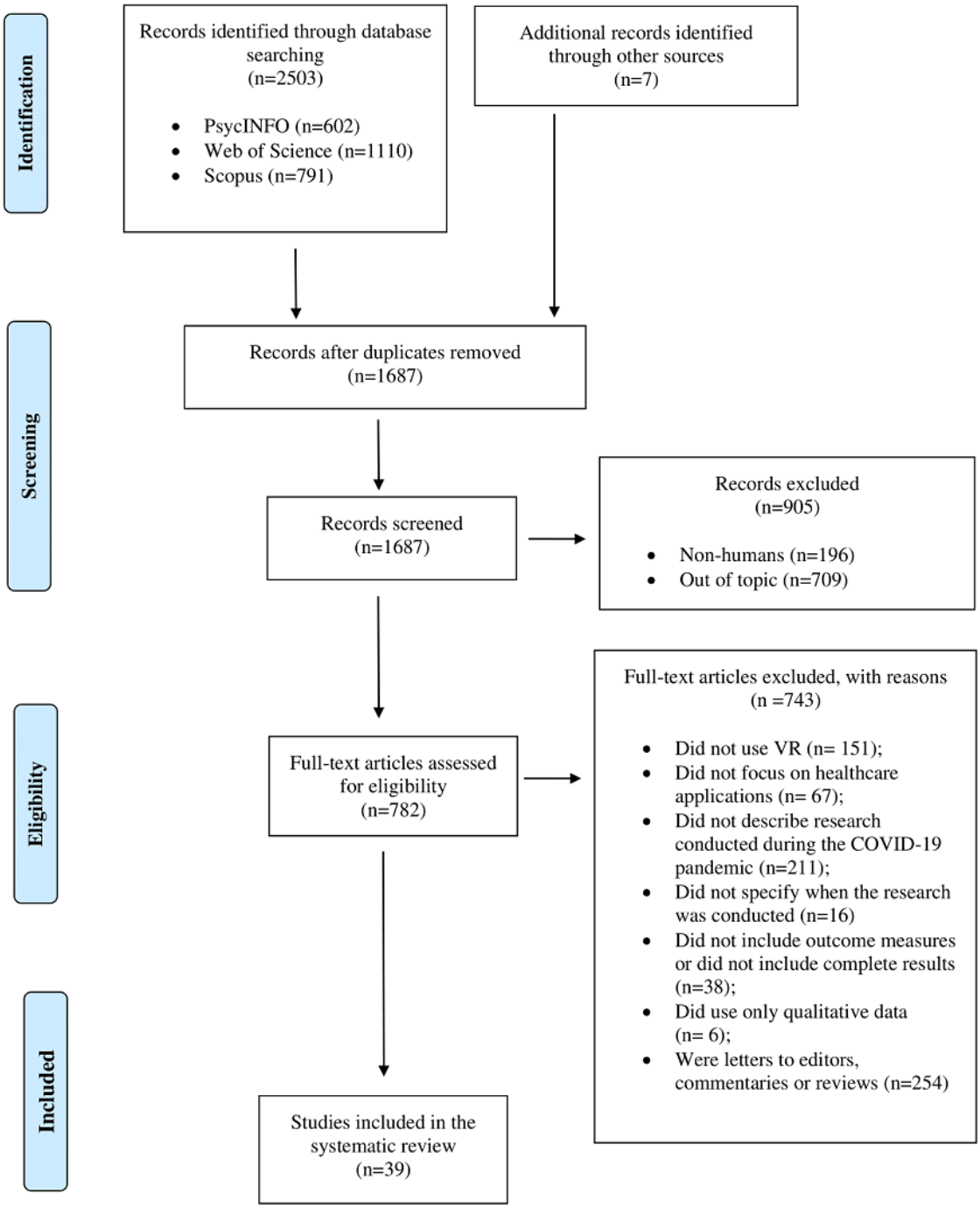
Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flow chart. VR: virtual reality.



Quality Assessment Outcomes

Interrater reliability was 0.827, representing substantial agreement [67]. Within this systematic review, the distribution of MMAT scores varied significantly with the study design (Table 2). Nineteen studies (49%) met the MMAT quality assessment score of 75% or above, implying that much of the research in this area is of high quality (Multimedia Appendix 1). Nevertheless, the quality scores varied substantially according to the study design.

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Table 2. Study design and Mixed Methods Appraisal Tool score distribution.

MMAT[a] score distribution	References	Value, n (%)
Quantitative randomized controlled trial (N=4)		
0	N/A[b]	0 (0)
25	N/A	0 (0)
50	[68,69]	2 (50)
75	N/A	0 (0)
100	[70,71]	2 (50)
Quantitative nonrandomized study (N=10)		
0	N/A	0 (0)
25	[72]	1 (10)
50	[73-77]	5 (50)
75	[78-81]	4 (40)
100	N/A	0 (0)
Quantitative descriptive study (N=19)		
0	N/A	0 (0)
25	[48,82-84]	4 (21)
50	[49,85-89]	6 (32)
75	[90-94]	5 (26)
100	[95-98]	4 (21)
Mixed methods study (N=6)		
0	[99]	1 (17)
25	N/A	0 (0)
50	[100]	1 (17)
75	[101,102]	2 (33)
100	[103,104]	2 (33)

[a]MMAT: Mixed Methods Appraisal Tool.

[b]N/A: not applicable.

Study Characteristics

Study Outcomes

Seventeen studies focused on the applications of VR during the COVID-19 pandemic to treat different health conditions, while 22 studies investigated its use for medical education and training (Multimedia Appendix 2).

Treatment

Ten studies showed the usefulness of VR for reducing stress, anxiety, and depression during the COVID-19 pandemic, and there were several findings. First, a self-administered at-home VR-based intervention through low-cost HMDs was useful during the COVID-19 lockdown for diminishing depression levels, stress levels, general distress, and perceived stress in healthy individuals up to the 2-week follow-up [74]. Second, immersive VR experiences showing calming nature scenes (ie, VRelax and Tranquil Cinematic-VR simulation) were helpful in reducing perceived stress among COVID-19 intensive care unit (ICU) health care workers [80,81]. Third, guided meditation and exploration of natural environments using immersive VR were highly satisfactory for patients recovering in a COVID-19 ICU, with perceived benefits in coping with isolation and loneliness [49]. The ICU staff considered VR logistically and operationally feasible [49]. Fourth, remote reminiscence training conducted during the first months of the COVID-19 pandemic using immersive VR diminished state anxiety without serious side effects (ie, nausea, dizziness, and headache) in patients with mild cognitive impairment [91]. Fifth, immersive VR exposure therapy showing scenes related to COVID-19 was effective in diminishing anxiety symptoms among patients with chief complaints of fear of COVID-19 [85], and in reducing levels of posttraumatic stress disorder (PTSD), anxiety, and depression among patients treated in the ICU due to COVID-19 [96]. The use of VR in the ICU was considered by patients to be feasible, and improved their satisfaction with and ratings of the ICU after care [71]. Sixth, immersive VR showing 360° YouTube videos reduced depressive symptoms in an adult with mild depressive disorder [95]. Seventh, 360° virtual tourism experiences diminished perceived stress among healthy young adults [92].

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VR has also been used as a distraction tool for pain management during the COVID-19 pandemic. A self-administered daily at-home immersive VR-based program (ie, EaseVRx) helped reduce pain intensity and interference with activity, stress, mood, and sleep over time among young adults experiencing chronic low back pain [70].

Four studies reported the efficacy of VR for promoting physical activities during the COVID-19 crisis. First, a desktop VR video game developed ad hoc and used at home improved movement performance and physical activity intensity among patients with cerebral palsy [79]. Second, commercial off-the-shelf VR video games (ie, "Box VR" and "NVIDIA VR Fun House") fostered physical exercise in 4 older people without adverse effects [90]. Participants reported that using such games was "positive and relaxing, and motivates you to exercise" [90]. Third, VR recreational use significantly increased during the COVID-19 lockdown period, and users expressed overwhelmingly positive opinions on the impact of VR activities on their mental and physical health. The self-reported intensity of physical activity was considerably more strenuous in VR users than in console users [86]. Fourth, VR fitness impacted individuals' physical and mental health, playing a substantial role in improving the overall quality of life and positively influencing the behavior and attitude of users [94].

Two studies provided early indications that Spanish-speaking (ie, Spain and Latin America) therapists have begun using VR to help their patients during social isolation due to COVID-19 [97,98], and 20% of the therapists indicated that they had used VR technology for remote psychological support [98].

Education and Training

Six studies revealed that VR represented a helpful learning and training tool during the COVID-19 pandemic in several areas. First, watching 360° videos on desktop displays effectively taught emergency medicine during the COVID-19 crisis [102]. Second, immersive VR showed relatively better outcomes regarding skills acquired, learning speed, and information retention rates than classroom training in a sample of frontline health workers [100]. Third, pediatric residents experienced a desktop VR-based training program as immersive, feasible, and realistic in terms of the clinic setting, and as a safe space to practice and learn new skills [101]. Fourth, VR-based pregraduation medical training was considered realistic with regard to the initial clinical assessment and diagnostic activity by medical students [48], even if a nonnegligible proportion of the students experienced difficulties in online access to the VR platform [48]. Fifth, an immersive social VR platform was reported as easy to use, helpful, and better than tele and video conferencing for remote multidisciplinary heart team meetings [82]. Sixth, applicants of a radiology residency reported positive attitudes toward a nonimmersive social VR platform [83].

Six studies successfully adopted VR for teaching various medical topics during the COVID-19 pandemic, and there were several findings. First, immersive VR was useful for teaching brain and spinal cord neuroanatomy and for practicing neurorehabilitation exercises [93]. Second, desktop VR–based training was used successfully for teaching nursing content [72,75,78] and urology [84]. Third, immersive VR experiences helped simulate pediatric ICU clinical scenarios, with some specific critiques regarding limited realism in some mechanical aspects of the simulation [99].

Six studies evaluated this technology to teach COVID-19–related skills to doctors and nurses, and as an educational tool for increasing public understanding of the COVID-19 crisis, and there were several findings. First, an immersive VR simulation (ie, COVID-19 VR Strikes Back) was at least as effective as traditional learning methods for training medical students regarding COVID-19–related skills [68]. Second, 2 immersive VR experiences, one involving wearing and stripping personal protective equipment [73] and the other involving the management of patients with respiratory infectious diseases due to COVID-19 [77], provided an effective and safe alternative to training nurses during the first year of the COVID-19 pandemic. Third, a virtual simulation of 2 patients (ie, COVID-19 and surgical trauma), which tried using desktop displays, helped nursing students bridge gaps in teaching and learning processes [104]. Fourth, a VR intervention using HMDs effectively increased COVID-19 vaccination intentions among unvaccinated young adults [69]. Fifth, VR, using desktop displays and HMDs, provided an effective educational tool for COVID-19 pandemic fundamental knowledge, increasing public understanding of the spread of the crisis [76].

Four studies investigated the adoption rate and the perception of VR in medicine during the COVID-19 pandemic. First, pediatric health care providers reported frequent modifications to existing simulation programs during the first months of the COVID-19 pandemic, including VR training [88]. Second, medical students mostly agreed that VR and online teaching compensated for the suspension of face-to-face medical education and reported that these technologies are the best alternatives to physical learning [89]. Third, the potential of VR for future teaching was rated low in a sample of medical students and lecturers, probably due to a lack of practical experience [87]. Fourth, high-fidelity immersive VR and specialized profession-specific resources were used heavily in medical education and training during the first year of the COVID-19 pandemic [103].

Study Design

Considering the entirety of the studies, the quantitative descriptive was the design of 19 studies (ie, 12 surveys and 7 case report studies). Ten studies adopted a quantitative nonrandomized design, 6 adopted a mixed methods design, and 4 adopted an RCT design (Table 2).

Populations

The number of participants ranged from 1 [95,96] to 4300 [94]. The study samples' characteristics are described in Table 3.

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Table 3. Study characteristics.

Characteristic	References	Value (N=39), n (%)
Study outcome		
Treatment	[49,70,71,74,79-81,85,86,90-92,94-98]	17 (44)
Education and training	[48,68,69,72,73,75-78,82-84,87-89,93,99-104]	22 (56)
Sample		
Students		
Medical students	[48,68,83,84,87,89,101,102]	8 (21)
Nursing students	[72,77,78,104]	4 (10)
Health professionals		
Doctors	[82,88,93,99,103]	5 (13)
Nurses	[73,75]	2 (5)
COVID-19 frontline workers	[80,81,100]	3 (8)
Mental health professionals	[97,98]	2 (5)
Patient health condition		
Recovered in the ICU[a] due to COVID-19	[49,71,96]	3 (8)
Depression	[95]	1 (2)
Chronic back pain	[70]	1 (2)
Cerebral palsy	[79]	1 (2)
Mild cognitive impairment	[91]	1 (2)
Chief complaints of fear of COVID-19	[85]	1 (2)
General population		
Healthy individuals	[69,74,76,86,90,92,94]	7 (18)
Age range		
Under 12 years old	N/A[b]	0 (0)
12-18 years old	[79]	1 (2)
18-35 years old	[68,69,72,74,75,78,80,86,87,89,92,94,101,104]	14 (36)
36-55 years old	[70,81,85,95,97,98]	6 (15)
Over 55 years old	[71,90,91,96]	4 (10)
Unspecified	[48,49,73,76,77,82-84,88,93,99,100,102,103]	14 (36)
Gender		
Both male and female	[68-72,74,75,77-82,85,86,89,91,92,94,97,98,101,102,104,105]	24 (62)
Male only	[90,95,96]	3 (8)
Female only	N/A	0 (0)
Unspecified	[48,49,73,76,83,84,87,88,93,99,100,103]	12 (31)
Nationality		
Europe	[48,68,69,71,74,81,82,84,86,87,89,90,96-98,102-104]	18 (46)
North America	[49,70,72,73,80,83,95,99,101]	9 (23)
South America	[79]	1 (2)
Asia	[75-78,85,91,92,94]	8 (20)
Africa	[93,100]	2 (5)
Oceania	N/A	0 (0)
Various	[88]	1 (2)

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Characteristic	References	Value (N=39), n (%)
Outcome measures		
Self-report questionnaire	All	39 (100)
Performance task	[68,78,79]	3 (8)
Semistructured interview	[95,101,104]	3 (8)
User session data	[95,104]	2 (5)
Focus group	[104]	1 (2)
Knowledge task	[72,73,75-77,100]	6 (15)
Physiological data	[73]	1 (2)

[a]ICU: intensive care unit.

[b]N/A: not applicable.

Outcome Measures

All the studies used self-reported questionnaires. Twenty-three studies adopted only this type of measure, while 16 studies also used other instruments, including performance tasks, semistructured interviews, knowledge tasks, users' session data, focus groups, and physiological data (see Table 3 for details).

VR Characteristics

Of the 39 studies included, 31 tested the efficacy of specific VR systems (Table 4), while 8 investigated the general use of VR in different samples (eg, mental health professionals and doctors) (Multimedia Appendix 3) [86-89,94,97,98,103].

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Table 4. Virtual reality characteristics.

Characteristic	References	Value (N=31), n (%)
Immersion		
High	[49,68-71,73,77,80-82,84,85,90,91,93,95,96,99,100]	19 (61)
Medium	N/A[a]	0 (0)
Low	[48,75,78,79,83,92,101,102,104]	9 (29)
Both high and low	[72,74,76]	3 (10)
Type of HMD[b]		
PC-based	[68,70,73,76,82,85,90,93]	8 (36)
Console-based		
Mobile	[72,74,84]	3 (14)
Standalone	[49,69,71,77,80,81,91,95,99]	9 (41)
Unspecified	[96,100]	2 (9)
Content		
Virtual environments	[68,69,73,75-77,82,83]	8 (26)
360° videos or photos	[71,72,74,80,81,84,91,92,95,96,102]	11 (35)
Embodied virtual agents	[48,78,99,101,104]	5 (16)
VR[c] video games	[79,90]	2 (6)
Hybrid	[49,70,93,100]	4 (13)
Unspecified	[85]	1 (3)
User mode		
Single user	[48,49,68-81,84,85,90-93,95,96,99-102,104]	29 (93)
Multiuser	[82,83]	2 (7)
Site of use		
Face-to-face	[49,68,70,71,73,76-78,80-82,84,85,90,92,93,96,99,100]	19 (61)
Remotely	[48,69,74,79,83,91,95,101,102,104]	10 (32)
Both	[72]	1 (3)
Unspecified	[75]	1 (3)
Time of use (in total)		
<10 minutes	[80,81,91-93,99]	6 (19)
11-60 minutes	[71,73,76-79,90,95,101]	9 (29)
61-180 minutes	[72,74,83,100]	4 (13)
>180 minutes	[48,70]	2 (6)
Unspecified	[49,68,69,75,82,84,85,96,102,104]	10 (32)

[a]N/A: not applicable.
[b]HMD: head-mounted display.
[c]VR: virtual reality.

Level of Immersion

Nineteen studies used a VR system with high immersion (ie, immersive VR), while 9 tested a system with low immersion (ie, desktop VR). Three studies adopted both immersive and desktop VR systems [72,74,76]. No study used semi-immersive VR systems (Table 4).

Types of HMDs

Of the 22 studies that used an HMD, standalone systems were the most popular, with 9 studies using them. Eight studies adopted PC-based VR systems, 3 studies used mobile VR systems [72,74,84], and 2 studies did not specify the model of HMD [96,100] (Table 4).

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Content

The most adopted VR content was 360° videos or photos, used in 11 studies. Eight studies used virtual environments, 2 studies adopted VR video games [79,90], 5 studies used embodied agents [48,78,99,101,104], 4 studies used hybrid content (ie, a mix of 360° videos or photo and virtual environments or VR video games) [49,70,93,100], and 1 study did not specify the content [85] (Table 4).

User Mode

The virtual content was of the single-user type in 29 studies and was of the multiuser type in 2 studies [82,83] (Table 4).

Site of Use

Nineteen studies used VR through face-to-face experiments, 10 used it remotely, and 1 used it both face-to-face and remotely [72]. Finally, 1 study did not specify the site of use [75] (Table 4).

Time of Use

In 21 studies reporting the number of sessions using VR, the mean number of sessions was 4.1, ranging from 1 (eg, [91,92,99]) to 56 sessions [70]. The number of minutes spent using VR differed among studies from about 5 minutes (eg, [79,99]) to up to 4 hours [48,70]. Ten studies did not indicate the exact time of use of VR (Table 4).

Discussion

Principal Findings

This systematic review examined studies conducted on VR applications in medicine during the COVID-19 pandemic, with a focus on using VR to treat health conditions and in medical education and training. After applying the inclusion criteria, 39 papers were included and analyzed.

From this systematic review, VR was found to be useful during the COVID-19 pandemic for reducing stress (eg, [75,80,96]), anxiety [91], depression [95], and pain [70], and promoting physical activity [79,90]. This technology has been successfully used in healthy people (eg, [74,86,92,94]); COVID-19 ICU health care workers [80,81]; patients with various diseases, including mild cognitive impairment [91], mild depressive disorders [95], and cerebral palsy [79]; chief complaints of fear of COVID-19 [85]; and individuals treated in the ICU due to COVID-19 [49,71,96].

VR has been successfully applied for decades to diminish stress, anxiety, depression, and pain [38,40,106-110]. Besides, this technology, especially immersive video games [111,112], stimulates physical activity [108], with long-term positive outcomes on mental and physical health [113,114]. What is new from the past, as noted in this review, is that VR is no longer used only in the specialist's office or at the hospital but is also used remotely. The release of current standalone and low-cost mobile VR systems, thanks to the high ease of use and limited costs, has made this technology feasible for everyday in-home use [115]. Studies from this review showed that VR during the COVID-19 pandemic has begun to be adopted into mainstream clinical practice for remote psychological support [97,98]. This fact appears relevant since VR home-based training represents new promising interventions for remote support [98,116,117].

From this review, not only VR environments developed ad hoc, but also commercial contents (eg, VR video games downloaded from the Steam platform, and 360° videos and photos available on YouTube) were useful for diminishing stress [92], anxiety [91], and depression [95], and for promoting physical activity [90]. These findings seem interesting since using commercial off-the-shelf VR video games and experiences for promoting mental health and physical activity could have several advantages, including their low cost and ready-to-use format, their advanced graphic quality, and the possibility to reach millions of individuals worldwide [107,118].

The second main result of this systematic review is that during the COVID-19 pandemic, VR was a helpful learning tool for medical education and training in several areas, including emergency medicine, nursing, pediatrics, radiology, and cardiology (eg, [100-102]). This technology has been successfully used for teaching various topics, including neuroanatomy and clinical anatomy (eg, [84,93]). VR has also been adopted to train COVID-19–related skills among doctors and nurses [68,73]. Studies that emerged from this systematic review showed that, where available, high-fidelity immersive VR was adopted heavily after the outbreak of the COVID-19 pandemic [88,103].

Several previous studies proved the usefulness of VR for the training of medical students and nurses [43] and for teaching many medical topics and procedures, such as clinical anatomy [41,45] and radiation oncology [42]. This technology is considered a superior educational modality in comparison to passive teaching methods, such as learning from a textbook, slideshow, or lecture, thanks especially to the greater involvement of individuals in the learning process [119-121].

This review, with regard to treatment, showed that during the COVID-19 pandemic, VR started to be used for medical education and training in face-to-face sessions and remotely. This flexibility of access allowed the adoption of this technology into medical education curricula for both in-person and home-based activities [122]. Medical students mostly agreed that online teaching using VR compensated for the suspension of face-to-face medical education and reported this technology as the best alternative to physical learning [89].

Some studies that emerged in this review used content in multiuser VR, including social VR platforms [82]. Such VR environments are an emerging diverse group of multiuser online applications creating new opportunities for remote simulation and communication, and facilitating and extending the existing communication channels of the physical world [123,124]. Although its exploration has been limited so far, education using social VR will be increasingly relevant in the next few years. Indeed, major technology companies are making huge investments in the so-called "metaverse" (ie, a simulated digital environment that incorporates VR and other technologies, including augmented reality and artificial intelligence, to build spaces where users can interact as in the actual world) [125]. "Metaversities" could become the universities of the future [126].

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In this systematic review, VR was also an effective educational tool for increasing public understanding and knowledge of the COVID-19 pandemic [76] and COVID-19 vaccination intentions [69]. This result, in line with previous literature [127,128], stresses the potential of VR as a useful and innovative tool for promoting scientific and medical knowledge among the general population. VR can improve health awareness and assist in health-related decision-making for the general population [129], increasing the overall motivation and engagement and leading to a more effective transfer of medical knowledge and comprehension of information [130,131]. In turn, this could improve individuals' overall health, decrease hospitalization rates, and save long-term physician consultation costs [129].

Moreover, studies from this systematic review showed the usefulness of VR for treating health problems and for medical education and training in both the high (ie, immersive VR) and low immersion (ie, desktop VR) formats. This result appears important as these VR systems have very different characteristics and costs [132-134]. On the one hand, as emerged from studies included in this review (eg, [68,70]), immersive VR offers advantages over desktop VR [62,135]. However, desktop VR has the main advantages of being more readily usable and accessible, and having a lower cost.

Various types of HMDs (ie, PC-based, mobile, and standalone) and contents (ie, 360° videos and photos, virtual environments, VR games, and embodied virtual agents) have been used with positive results in medicine during the COVID-19 crisis (eg, [48,73,101]). This underscores how nowadays it is possible to choose among different VR hardware and software. To select the potentially most effective ones, it is critical to reason about the specific goal of VR use [136]. For example, in the case of VR for relaxation, it may be sufficient to include a low-cost mobile system and 360° videos or commercial off-the-shelf VR games. The same is true when VR is adopted to offer doctors and nurses "soft skills" (eg, problem-solving, communication, and interpersonal skills) training. On the other hand, in the case where VR is used for complex operations, simulation training, a PC-based system, haptic devices, and specially created virtual content should be used. In fact, in this case, the graphical and sensory fidelity of VR are crucial [137,138].

Barriers for Using VR in the Health Care Sector

In addition to offering data in favor of the usefulness of VR in the health care sector, this review also raises some critical reflections on the possible limits of using this technology for these aims.

First, some health care workers experienced difficulties in using VR [48]. Due to a lack of knowledge of this technology, many individuals may find it challenging to use VR. To overcome the mentioned obstacle, governments and other societal bodies (eg, medical societies, medical schools, and residency training programs) should provide information about VR (eg, through training courses dedicated to health care practitioners and mental health professionals). They should offer clear guidelines for correctly using this technology in mental health, and medical education and training [15].

Second, when the graphic quality of the virtual experience was perceived as too low, users had difficulties comprehending a target scenario [73,87]. To prevent graphical or technical problems (eg, breakdown or problems with interaction) [139,140], with potential detrimental effects on treatment and learning outcomes [137,141], the principles and practices of user-centered design are recommended [142,143]. Many VR-based treatment, and medical education and training programs are currently taking a technology approach rather than a human-centered approach, which can lead to limited impact of VR in these fields. Due to the close bond between the user and the system within virtual environments, it may be impossible to segregate human factors from design issues when striving to achieve the potential of VR [144]. For this reason, it appears critical that a psychologist with expertise in human-computer interaction always be included in the team developing virtual experiences for the medical field.

Third, a primary issue in using this technology in the mental health panorama is related to its costs. The price of HMDs range from US $300 to US $1500. In the case of VR content developed ad hoc, the costs for implementation are high. One way to overcome the economic barrier of VR could be to use standalone or low-cost mobile systems [115,145] and, whenever possible, commercially available content [107,118]. Another solution could be providing hospitals with a certain number of VR systems to be available for their patients and staff for free [15].

Recommendations for Future Research

More studies should be undertaken to expand the limited literature on home-based VR for treatment, and medical education and training. Multiuser VR platforms could be studied more deeply in education and as tools to implement future interventions for treating mental and physical health conditions. More research should be conducted to test the efficacy of commercial off-the-shelf VR experiences for treatment and in educational settings. Limitations and possibilities of VR systems with high versus low immersion require further investigation, for example, through RCT studies comparing their effectiveness for clinical or learning outcomes. It might be worth investigating the longer-term effects of VR on such outcomes. Finally, the number of desired or needed VR sessions and the specific time to spend using VR remain matters of debate.

Limitations

This review summarizes health care-targeted applications of VR during the COVID-19 pandemic based on specific keywords used in the search string, the databases included, and the review's time period. Therefore, certain articles could have been missed. Second, only articles written in English and peer reviewed were included. Hence, preprints and gray literature were left out, which may have introduced some biases. Third, a meta-analysis was not possible due to the heterogeneity of the included studies. Fourth, the quality assessment performed using the MMAT suggests that even if much of the research in this area is of high quality, methodological concerns are significant issues for many studies.

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Conclusions

VR has been applied frequently during the COVID-19 pandemic in medicine, with positive effects for treating several health conditions and for medical education and training. Some barriers need to be overcome for a broader adoption of VR in the health care panorama. Based on these findings, it is possible to offer certain VR-based programs even remotely for therapeutic or educational purposes, and not only VR environments developed ad hoc, but also commercial content can be helpful in clinical or educational support. Moreover, VR-based interventions have the potential to be used effectively for the treatment of several mental and physical conditions, as well as for medical education and training in both immersive and desktop systems. Various VR contents are helpful in treating health problems and for medical education and training, including 360° videos and photos, VR games, and embodied virtual agents.

Authors' Contributions

FP conceived the work and wrote the first draft of the manuscript. All the authors contributed to manuscript revision, and read and approved the submitted version of the manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1
Mixed Methods Appraisal Tool evaluation.
[DOCX File , 38 KB - games_v10i4e35000_app1.docx]

Multimedia Appendix 2
Study characteristics.
[DOCX File , 59 KB - games_v10i4e35000_app2.docx]

Multimedia Appendix 3
Virtual reality characteristics.
[DOCX File , 30 KB - games_v10i4e35000_app3.docx]

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Abbreviations

HMD: head-mounted display
ICT: information and communication technology
ICU: intensive care unit
MMAT: Mixed Methods Appraisal Tool
RCT: randomized controlled trial
VR: virtual reality

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Review

The Effects of Virtual Reality Training on Balance, Gross Motor Function, and Daily Living Ability in Children With Cerebral Palsy: Systematic Review and Meta-analysis

Cong Liu[1], MD; Xing Wang[1], PhD; Rao Chen[1], MD; Jie Zhang[2], PhD

[1]School of Physical Education and Sport Training, Shanghai University of Sport, Shanghai, China

[2]Department of Physical Education, Donghua University, Shanghai, China

Corresponding Author:
Jie Zhang, PhD
Department of Physical Education
Donghua University
2999 Renmin North Road
Songjiang District
Shanghai, 201620
China
Phone: 86 15221857691
Email: j202166@163.com

Abstract

Background: The increasing number of children with cerebral palsy (CP) has a serious impact on individuals, families, and society. As a new technology, virtual reality (VR) has been used in the rehabilitation of children with CP.

Objective: This study aimed to systematically evaluate the effect of VR training on balance, gross motor function, and daily living ability in children with CP.

Methods: PubMed, Embase, The Cochrane Library, Web of Science, and China National Knowledge Infrastructure databases were searched by computer, with the search period being from the establishment of each database to December 25, 2021, to collect randomized controlled trials (RCTs) on the effects of VR training on balance, gross motor function, and daily living ability in children with CP. The Cochrane risk of bias assessment tool was used to conduct quality assessment on the included literature, and RevMan software (version 5.3) was used to analyze data.

Results: A total of 16 articles were included, involving 513 children with CP. VR training can improve the balance function (Pediatric Balance Scale: mean difference 2.06, 95% CI 1.15-2.97; $P<.001$; Berg Balance Scale: mean difference 3.66, 95% CI 0.29-7.02; $P=.03$) and gross motor function (standardized mean difference [SMD] 0.60, 95% CI 0.34-0.87; $P<.001$) of children with CP. However, there is still certain disagreement on the impact on daily living ability (SMD 0.37, 95% CI –0.04 to 0.78; $P=.08$); after removing the source literature with heterogeneity, VR training can improve the daily living ability of children with CP (SMD 0.55, 95% CI 0.30-0.81; $P<.001$).

Conclusions: VR training can significantly improve the balance function and gross motor function of children with CP, but the effect on the daily living ability of children with CP remains controversial.

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KEYWORDS

virtual reality; cerebral palsy; balance; gross motor activities; activities of daily living; meta; motor; children; pediatrics

Introduction

Cerebral palsy (CP) is a nonprogressive, persistent syndrome occurring in the brain of the fetus or infant [1]. The prevalence of CP is very high worldwide, and the prevalence can increase to 20-30 times in preterm or low–birth-weight newborns [2]. There are about 6 million children with CP in China, and the number is increasing at a rate of 45,000 per year [3]. Insufficiency of movement and abnormal posture are core symptoms of CP, and about 80% of children with CP have dyskinesia [4]. In addition, children with CP also have cognitive, communication, and perception-behavioral disorders; epilepsy; and other problems, which greatly limit their social participation

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and seriously affect their physical and mental health and quality of life.

Virtual reality (VR) refers to a virtual environment that is generated by a computer and can be interacted with. VR can mobilize the visual, auditory, tactile, and kinesthetic organs of children with CP, so that they can actively participate in the rehabilitation exercise. In this way, the central nerve conduction and peripheral motor control of children can be coordinated and unified, which is conducive to the rehabilitation of children [5]. Choi et al [6] conducted VR training for 40 children with CP for 4 weeks, 5 times a week, for 30 minutes each time. The study reported that compared with regular rehabilitation, the children in the VR group showed better results. Gagliardi et al [7] conducted a longitudinal study on 16 children with CP for 4 weeks, 5 times a week, for 30 minutes each time, and the results showed that the children's walking ability and gross motor function improved. However, there was no significant change in daily living ability. In addition, a recent systematic review also showed that the combination of VR training and conventional rehabilitation training indicates better pure conventional rehabilitation training [8].

It has become a focus of scholars in China and abroad to improve the motor ability, abnormal posture, and quality of life of children with CP. Previous meta-analyses have shown that VR can significantly improve children's hand function, balance function, gross motor function, and walking function [8-11]. The main problem this study intended to address is (1) whether VR training can significantly improve children's balance and gross motor function after adding new evidence; (2) whether VR training can significantly improve children's daily living ability; (3) whether the improvement of VR training on children with different types of CP is different; (4) whether the improvement of different types of VR on children with CP is different; and (5) whether different frequencies and periods of VR training have different improvement on children with CP. Address these problems will provide a basis for the formulation of accurate VR training program for children with CP.

Methods

This study followed the requirements of the International Meta-analysis Writing Guidelines (The PRISMA [Preferred Reporting Items for Systematic Reviews and Meta-Analyses] statement for studies that evaluate health care interventions: explanation and elaboration) for the selection and use of methods.

Literature Retrieval Strategy

In this study, 2 researchers independently retrieved 5 databases including PubMed, Embase, The Cochrane Library, Web of Science, and China National Knowledge Infrastructure (CNKI) to find randomized controlled trials (RCTs) of VR training effects on balance, gross motor function, and daily living ability in children with CP. Moreover, the sources of the CNKI database were limited to Chinese Social Sciences Citation Index and Chinese Science Citation Database, and the retrieval dates of all databases were from the establishment of each database to December 25, 2021. Supplementation measures were the tracking of relevant systematic reviews and references of the included literature. The retrieval adopted the method of combining subject words with free words—the Boolean operators "AND" and "OR" were used to combine and connect—and was determined after repeated prechecks. English search terms included "cerebral palsy," "CP," "children of cerebral palsy," "cerebral palsy children," "virtual reality," "VR," "virtual environment," "video game," "clinical trial," "randomized controlled trial," etc. An example of the literature retrieval strategy for the PubMed database is given (Multimedia Appendix 1).

Inclusion and Exclusion Criteria

Inclusion Criteria

The inclusion criteria were as follows:

1. Population for research objects: clinically diagnosed children with spastic CP; their race and gender are not limited, and they are aged <16 years
2. Interventions for experimental group: VR training, VR training combined with conventional rehabilitation training, or VR training added on the basis of control group training
3. Comparison for control group interventions: daily physical activities, balance training, conventional rehabilitation training, or comprehensive rehabilitation training, etc
4. Outcome for outcome indicators: balance function was evaluated by Berg Balance Scale (BBS) and Pediatric Balance Scale (PBS); gross motor function was evaluated using the Gross Motor Function Measure Scale (GMFM), including GMFM-66, GMFM-E and GMFM-88; and the ability of daily living was assessed by Pediatric Evaluation of Disability Inventory (PEDI) and The Functional Independence Measure for Children (WeeFIM)
5. Study design for study type: RCTs

Exclusion Criteria

The exclusion criteria were as follows: non-RCTs; republished papers or papers with poor-quality evaluation; literature not in Chinese and English; full text not available; outcome indicators did not meet the requirements of this study or data could not be extracted; and intervention group content did not meet the requirements.

Literature Screening and Data Extraction

In this study, 2 researchers independently retrieved literature from 5 databases and downloaded the retrieved literature into EndNote X9 software (Clarivate) in batches. After all the documents from the 5 databases were retrieved, duplicate documents were first removed in Endnote X9 software. Second, preliminary screening was carried out by reading the title and abstract. Third, the papers were screened according to the inclusion and exclusion criteria of this study. Finally, full-text readings were conducted to identify studies for final inclusion.

In all, 2 researchers extracted the data of the basic information and outcome indicators of the included papers and contacted the original author by email for unclear or missing data in the study. When the information extracted by 2 researchers was inconsistent, a third researcher would participate in a discussion to reach a consensus. The extracted information included basic

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information (author, year, country, sample size, type of CP, and patient age); experimental characteristics (intervention content, single intervention duration, frequency, and cycle); and outcome indicators. The researchers set up a table by reading the articles that met the inclusion criteria in detail and recording the relevant information.

Quality Evaluation of Included Literature

This study used The Cochrane Collaboration's Tool for Assessing Risk of Bias to analyze the literature using 7 methods: random sequence generation, allocation concealment, blinding of subjects and researchers, blinding of raters, incomplete outcome data, selective reporting, and other biases. These analysis results were categorized into 3 types of quality evaluation: low risk, unclear, and high risk. This process was carried out by 2 researchers independently. In case of disagreement, a third researcher would join in to discuss and make a decision. The quality of the literature was divided into 3 levels: grade A (low risk, meeting 4 or more items); grade B (low risk, meeting 2 or 3 items); and grade C (low risk, meeting 1 or no items, bias likely to occur) [12].

Data Analysis

Data analysis was performed using RevMan software (version 5.3; Cochrane) and following the PRISMSA guidelines. The Q statistic test (P value) and I^2 were used to test for heterogeneity. If there had been statistical heterogeneity between studies (I^2>50%; P<.10), a random effects model would have been used for meta-analysis; otherwise, the fixed effects model would have been used. In this study, GMFM-66, GMFM-88, and GMFM-E were combined for gross motor function, and PEDI and WeeFIM were combined for daily living ability. Therefore, standardized mean difference (SMD) was used to calculate the indicators for gross motor function and daily living ability, and the mean difference (MD) was used to calculate the other indicators. There were no significant differences in the outcome variables between the groups in each comparison at baseline. At the end of the experiment, we chose scale scores of both the intervention group and the control group as the effect size, which reflects the intervention effect. Each effect size was given a point estimate and 95% CI. When P<.05, there was a significant difference between the intervention group and the control group, proving that the meta-analysis results were statistically significant. Publication bias testing was performed using Stata software (version 16.0; StataCorp) [13].

Results

Literature Retrieval Results

In all, 2 researchers searched 5 databases, including PubMed (n=82), Embase (n=191), The Cochrane Library (n=147), Web of Science (n=359), and CNKI (n=11). A total of 793 papers were retrieved, including 11 Chinese papers, 759 English papers, and 3 papers [14-16] from the previous systematic review of other people. After duplicate papers were excluded by Endnote X9 software, there were 640 papers left. Subsequently, 65 papers remained after primary screening, and lastly, 16 papers were left after the full-text rescreening [14-29]. As a result, 16 RCTs were finally included, as shown in Figure 1.

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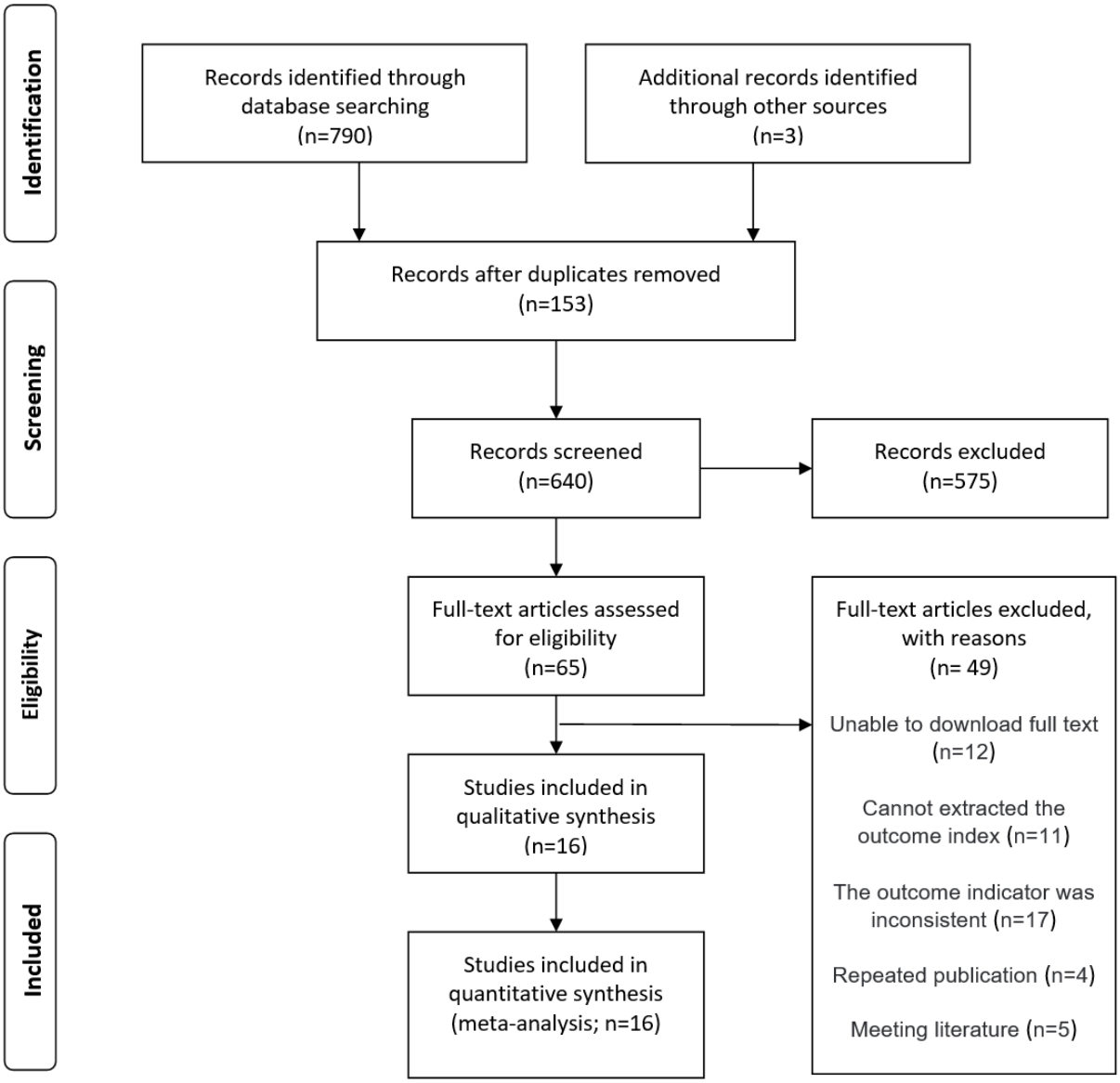
Figure 1. Literature screening process.



Basic Features of Included Studies

A total of 16 articles representing16 RCTs were included—more specifically, 5 Chinese articles and 11 English articles. The publication period is from 2013 to 2021, and the countries of publication are China, Turkey, India, and South Korea. A total of 513 children with CP were included, and the CP types included spastic hemiplegia and spastic diplegia. The intervention of the experimental group included virtual time-limited training and the combination of VR training and regular rehabilitation training, etc; and the intervention of the control group included daily physical activities and regular rehabilitation training. The intervention duration of VR training was from 15-60 minutes, the frequency was from 2-6 times a week, and the cycle was from 3-12 weeks. (Multimedia Appendix 2).

Quality Evaluation of the Included Literature

A total of 16 RCTs were included in this study, and their risk of bias was shown in Multimedia Appendix 3. All 16 RCTs described the generation of random sequences, among which 6 RCTs [14,17,19,21,23,24] described methods of allocation concealment, 6 RCTs [18-23] applied the blinding method for researchers and subjects, 6 RCTs [17,19-21,23,24] used the blinding method for raters, and all 16 RCTs had complete data and did not selectively report them.

Meta-analysis Results

VR Effects on the Balance Function of Children With CP

A total of 126 cases of children with CP in 6 RCTs participated in the VR training and had relevant scoring conducted by using PBS evaluation, as shown in Figure 2. The results of the heterogeneity test (I^2=33%; P=.19) indicated that there was no statistical heterogeneity among the studies, so the fixed effects model was used for analysis. Meta-analysis results showed that VR training was able to improve the PBS scores of children with CP (MD 2.06, 95% CI 1.15-2.97; P<.001), indicating that

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VR training could significantly improve the balance function of children with CP compared to the control group.

A total of 123 cases of children with CP in 3 RCTs participated in the VR training and had relevant scoring conducted by using BBS evaluation, as shown in Figure 3. Heterogeneity test results (I^2=67%; P=.05) indicated statistical heterogeneity between studies; therefore, the random effects model was used for analysis. Meta-analysis results showed that VR training was able to improve the BBS scores of children with CP (MD 3.66, 95% CI 0.29-7.02; P=.03), indicating that VR training was able to improve the balance function of children with CP significantly compared to the control group. Since only 3 papers were included in this analysis, so no sensitivity analysis was performed.

Figure 2. Forest plot of the effect of virtual reality on the Pediatric Balance Scale scores in children with cerebral palsy. IV: inverse variance.

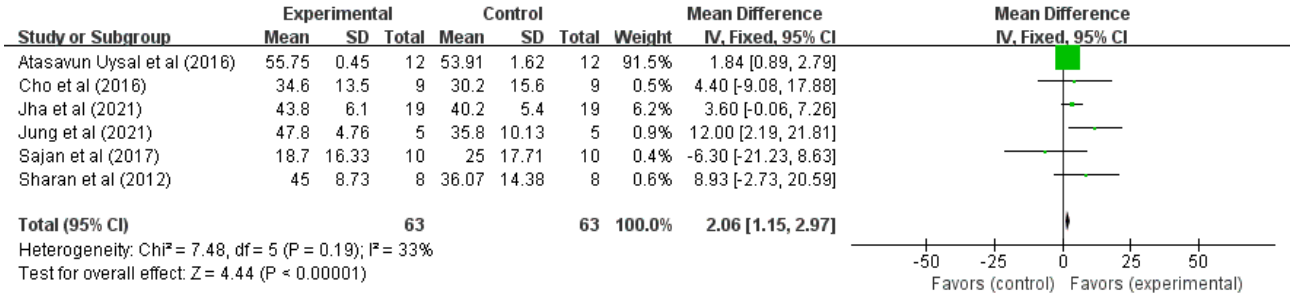
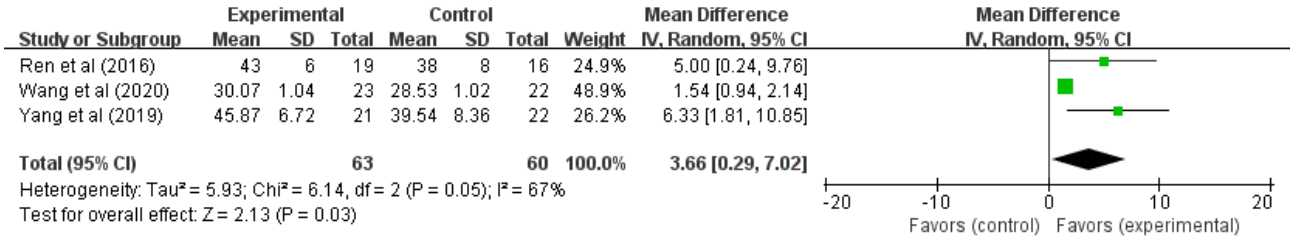


Figure 3. Forest plot of the effect of virtual reality on the Berg Balance Scale scores in children with cerebral palsy. IV: inverse variance.



Influence of VR on the Gross Motor Function of Children With CP

A total of 236 cases of children with CP in 7 RCTs participated in VR training for the impact on their gross motor function, as shown in Figure 4. Heterogeneity test results (I^2=5%; P=.39) indicated that there was no statistical heterogeneity between studies, so the fixed effects model was used for analysis. Meta-analysis results showed that VR training improved gross motor function in children with CP (SMD 0.60, 95% CI 0.34-0.87; P<.001), indicating that VR training could significantly improve gross motor function in children with CP compared to the control group.

A subgroup analysis in terms of CP type, training frequency, and period is shown in Table 1. The types of CP were divided into hemiplegia, diplegia, and other types, and the results showed that, compared to the control group, VR training only improved the gross motor function of children with hemiplegia significantly (P<.001). The training frequency was divided into ≤4 days/week and >4 days/week, and the results showed that, compared to the control group, VR training >4 days/week significantly improved the gross motor function of children with CP (P<.001). The training period was divided into <6 weeks and ≥6 weeks, and the results showed that, compared to the control group, both groups showed significant improvement on the gross motor function of children with CP (P<.001 and P=.002, respectively).

Figure 4. Forest plot of the effects of virtual reality on the gross motor function in children with cerebral palsy. IV: inverse variance.

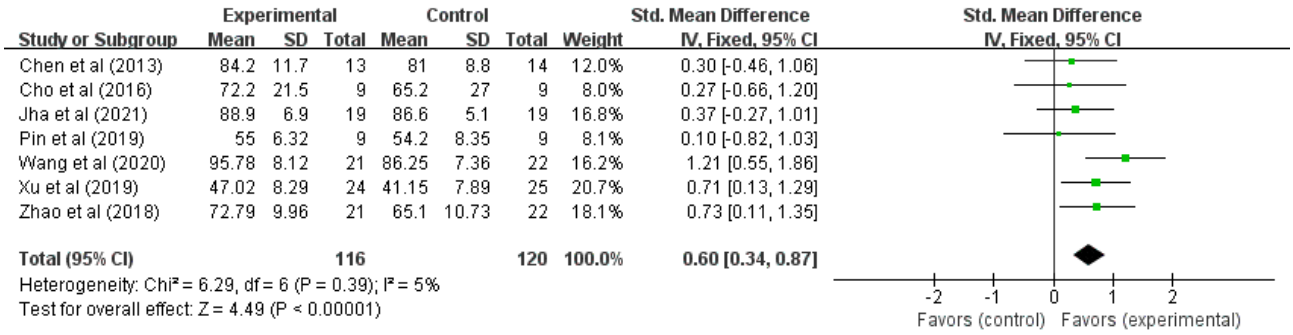


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Table 1. Subgroup analysis of the effects of virtual reality training on gross motor function in children with cerebral palsy.

Group	Study, n	I^2 (%)	Model	SMD[a] (95% CI)	*P* value
Type of cerebral palsy					
Hemiplegia	2	0	Fixed effects model	0.72 (0.30 to 1.14)	<.001
Diplegia	2	0	Fixed effects model	0.28 (–0.24 to 0.81)	.29
Other	3	52	Random effects model	0.64 (–0.00 to 1.29)	.05
Training frequency					
≤4 days/week	4	0	Fixed effects model	0.29 (–0.11 to 0.68)	.15
>4 days/week	3	0	Fixed effects model	0.86 (0.51 to 1.22)	<.001
Training cycle					
<6 weeks	2	0	Fixed effects model	0.72 (0.30 to 1.14)	<.001
≥6 weeks	5	31	Fixed effects model	0.53 (0.19 to 0.87)	.002

[a]SMD: standardized mean difference.

Effect of VR on the Daily Living Ability of Children With CP

A total of 274 children with CP from 7 RCTs participated in the research on the VR training effect on the daily living ability of CP children, as shown in Figure 5. The results of the heterogeneity test (I^2=64%; *P*=.01) indicated that there was statistical heterogeneity among the studies, so the random effects model was used for analysis. Meta-analysis results showed that VR training did not improve the daily living ability of children with CP (SMD 0.37, 95% CI –0.04 to 0.78; *P*=.08), indicating that, compared to the control group, VR training had no effect on the daily living ability of children with CP. There was no advantage in improving the daily living ability of children with CP.

To explore sources of heterogeneity, a sensitivity analysis was performed by successive elimination of studies (see Table 2). After excluding Acar et al [14], there was no significant change in heterogeneity (SMD 0.45, 95% CI 0.07-0.89; *P*=.02), indicating that, compared to the control group, VR training had a significant effect on the daily living ability of children with CP. After excluding Atasavun Uysal et al [24] (I^2=36%; *P*=.16), the fixed effects model was used for analysis (SMD 0.55, 95% CI 0.30-0.81; *P*=.001), indicating that, compared to the control group, the VR training significantly improved the daily living ability of children with CP. After excluding other studies, there was no significant change in heterogeneity, and the *P* values of the effect sizes were all greater than .05. Therefore, Atasavun Uysal et al [24] may be a source of heterogeneity.

After excluding Atasavun Uysal et al [24], a total of 250 cases of children with CP in 6 RCTs participated in VR training on their daily living ability, as shown in Figure 6. The results of the heterogeneity test (I^2=36%; *P*=.16) indicated that there was no statistical heterogeneity among the studies, so the fixed effects model was adopted for analysis. Meta-analysis results showed that VR training significantly improved the daily living ability of children with CP (SMD 0.55, 95% CI 0.30-0.81; *P*<.001), indicating that, compared to the control group, VR training was able to significantly improve the daily living ability of children with CP.

A subgroup analysis of VR system type, training frequency, and training period is presented in Table 3. The types of VR systems were divided into Wii (Nintendo), Kinect (Microsoft), and other types. The results showed that, compared to the control group, only the Kinect system could significantly improve the daily living ability of children with CP (*P*<.001). Additionally, "other types" only had 1 study and is therefore not representative. The training frequency was divided into ≤4 days/week and >4 days/week, and the results showed that, compared to the control group, both groups significantly improved the daily activities of children with CP (*P*=.02 and *P*<.001, respectively). The training period was divided into ≤6 weeks and >6 weeks, and the results showed that, compared to the control group, VR training for >6 weeks significantly improved the daily activities of children with CP (*P*=.005).

Figure 5. Forest plot of the effects of virtual reality on the daily living ability in children with cerebral palsy. IV: inverse variance.

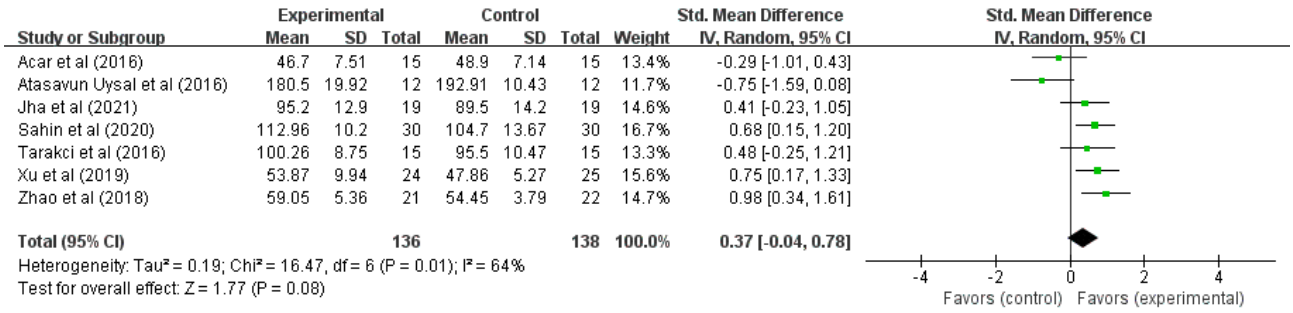

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Table 2. Combined effect of daily living ability after excluding individual studies.

Study eliminated	SMD[a] (95% CI)	*P* value (combined effect)	I^2 (%)	*P* value (heterogeneity)	Model
Acar et al [14], 2016	0.48 (0.07 to 0.89)	.02	58	.03	Random effects model
Atasavun Uysal et al [24], 2016	0.55 (0.30 to 0.81)	.001	36	.16	Fixed effects model
Jha et al [17], 2021	0.35 (–0.13 to 0.84)	.15	70	.006	Random effects model
Sahin et al [20], 2020	0.30 (–0.19 to (0.79)	.23	68	.009	Random effects model
Tarakci et al [23], 2016	0.34 (–0.13 to 0.82)	.16	70	.006	Random effects model
Xu et al [26], 2019	0.29 (–0.18 to 0.77)	.23	67	.01	Random effects model
Zhao et al [28], 2018	0.27 (–0.17 to 0.70)	.23	62	.02	Random effects model

[a]SMD: standardized mean difference.

Figure 6. Forest plot of the effects of virtual reality on the daily living ability in children with cerebral palsy (excluding Atasavun Uysal et al [24]). IV: inverse variance.

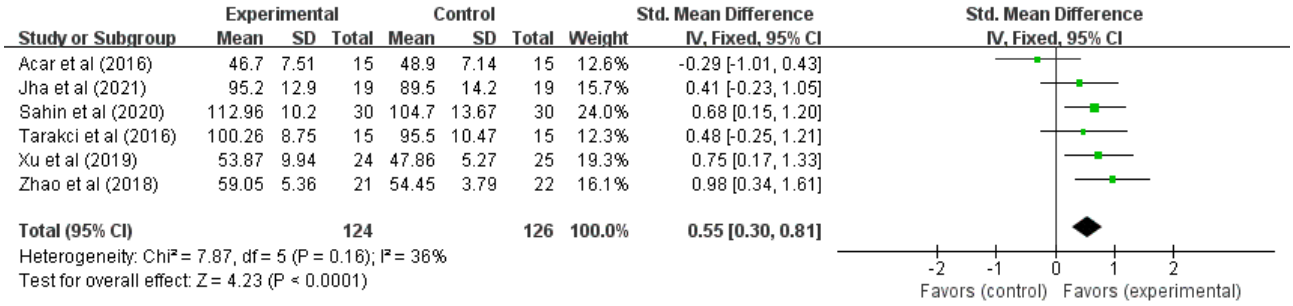

Table 3. Subgroup analysis of the effects of virtual reality training on daily living ability in children with cerebral palsy.

Group	Study, n	I^2 (%)	Model	SMD[a] (95% CI)	*P* value
Virtual reality system type					
Wii	2	54	Random effects model	0.09 (–0.66 to 0.85)	.81
Kinect	3	0	Fixed effects model	0.69 (0.35 to 1.03)	<.001
Other	1	N/A[b]	N/A	0.75 (0.17 to 1.33)	.01
Training frequency					
≤4 days/week	4	36	Fixed effects model	0.39 (0.07 to 0.70)	.02
>4 days/week	2	0	Fixed effects model	0.85 (0.42 to 1.28)	<.001
Training cycle					
≤6 weeks	4	60	Random effects model	0.48 (–0.03, to 1.00)	.06
>6 weeks	2	0	Fixed effects model	0.61 (0.19 to 1.03)	.005

[a]SMD: standardized mean difference.

[b]N/A: not applicable.

Testing of Publication Bias

Since the BBS indicators used in the study were limited, only the PBS, gross motor function, and daily living ability indicators were tested by Begg funnel plot. The test result of PBS was Z=0.75 (P_r>|z|=.45); the test result of gross motor function was Z=0.9 (P_r>|z|=.37); and the test result of daily living ability was Z=1.50 (P_r>|z|=.13). Therefore, there was no publication bias in this study (Multimedia Appendix 4).

Discussion

Principal Findings

VR technology is a new practical technology; it integrates computer software and hardware, artificial intelligence, sensing, simulation, and other scientific technologies to give users an immersive sense and can provide users with the ability to interact with virtual objects. At present, VR technology has been widely used in the field of medicine to promote the rapid recovery of patients [20-32].

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The balance function depends on the central nervous system in many aspects. In addition to the central nervous system injury, children with CP also have skeletal deformity, triceps spasm in the calf, increased muscle tension on one side, and clubfoot, which seriously affect the balance ability of children with CP [33,34]. VR training can enable children to actively complete hip flexion, abduction, and external rotation in a standing state, which is conducive to the improvement of balance function. VR training can also provide purposeful tasks and give sensory feedback, which is conducive to the recovery of neurological function— this in turn improves the balance function [35]. In this study, PBS and BBS were used to evaluate the balance function of children with CP. The results showed that VR training could significantly improve the balance function of children with CP compared to the control group, which are consistent with previous studies. Jaume-i-Capó et al [36] conducted VR game training for 9 adult patients with CP for 24 weeks, and the results showed that the balance function of the patients was significantly improved. Jelsma et al [37] conducted VR training (Nintendo Wii Fit) for 25 minutes, 4 times a week for 3 weeks on 14 children with CP, and the results showed that the balance and walking function of children with CP were significantly improved. Pourazar et al [38] conducted VR training for 10 children with CP for 20 times, and the results showed that the balance function of the experimental group was significantly improved compared to the control group.

VR training, which provides children with CP with a similar environment to the real world, gives a visual, auditory, and kinesthetic stimuli and interaction; activates the brain specific movement area; increases the blood flow of motor cortex; and prompts the cortical neural and cortex tissue improvement and restructuring. Therefore, the movement function of children can be compensated and activated, and motor function is improved [39]. In addition, VR training requires children to complete movements such as running and jumping to improve their motor function. In this study, GMFM was used to evaluate gross motor function in children with CP. The results showed that VR training was able to significantly improve gross motor function in children with CP compared to the control group. The findings are consistent with previous studies. Collange Grecco et al [40] performed VR training combined with continuous transcranial direct current stimulation on children with CP and found that gross motor function and gait were significantly improved. Burdea et al [41] conducted VR training for children with CP 3 times a week for 12 weeks and found that movement disorders in children with CP were significantly improved. In addition, a review also showed that VR training was beneficial to the improvement of gross motor function in children with CP [42]. The results of this study showed that VR training only significantly improved the gross motor function in children with hemiplegia but not in children with diplegia, which may be related to the limited studies involved.

In this study, WeeFIM and PEDI were used to evaluate the daily living ability of children with CP. The results showed that there was significant heterogeneity between studies and that VR training did not significantly improve the daily living ability of children with CP compared to the control group. To reduce the heterogeneity between studies, the method of successive elimination of studies was used for sensitivity analysis, and the results showed that the heterogeneity came from Atasavun Uysal et al [24]. After reading the full text of the paper again, it was speculated that the main reason was that the PEDI scoring method was using original scores instead of normative scores, which led to excessive heterogeneity among studies. After removing and combining the effect size, it was found that compared to the control group, the VR training group significantly improved the children's daily living ability, which was consistent with previous studies. Tarakci et al [23] conducted VR training twice a week for 20 minutes each time, for 12 weeks on 15 children with CP, and the results showed that compared to the control group, the children in the VR training group had significantly improved their daily living ability. You et al [43] conducted VR training on children with CP and found that the cerebral cortex related to self-feeding and dressing was improved. VR training may improve the daily living ability of children with CP for the following reasons: the virtual environment provided by VR training can be highly consistent with the real world, which is conducive to mobilizing all organs of children with CP and transferring skills acquired by children with CP to daily life; and VR training can provide a variety of sensory stimulation and feedback information, which is more novel than traditional rehabilitation. Therefore, children are more actively involved in rehabilitation training with higher compliance, which makes the connection of peripheral-central-peripheral nerve conduction pathways more frequent. All these improvements are beneficial to the rehabilitation of children with CP [44,45]. This study shows that the Kinect system has a more obvious improvement effect on children's daily living ability, whereas the Wii system has no obvious improvement effect on children's daily living ability. This finding may be due to the fact that the Kinect system more enriched than the Wii system, its sensory stimulation is more obvious, and the human-computer interaction is more natural and convenient. In addition, the results of this study showed that the longer the training cycle, the better the improvement of gross motor function and daily living ability of children with CP. Therefore, in future studies, the rehabilitation training time of children with CP should be extended.

Our study found that VR can improve balance function and gross motor function in children with CP, which is consistent with previous studies. After removing the literature with high heterogeneity [24], the results showed that VR can improve the daily living ability of children, which is also similar to previous studies. In addition, our study also found that the type of VR system, the type of CP, and the training time can all affect the rehabilitation of children.

Limitations

This study only included Chinese- and English-language literature; the indicators included were limited to GMFM, BBS, and PBS; and the number of studies included in several groups was relatively small in the subgroup analysis, so the conclusions obtained have certain limitations. The content of VR training is diverse; the content of regular rehabilitation is not consistent; and the duration, frequency, and cycle of training are also different, which may also be the reason for the heterogeneity of studies. Part of the literature included in this study did not

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clarify whether allocation concealment was used, the researchers or subjects were blinded, or the evaluators were blinded, so there may be bias in the research results.

Conclusions

Meta-analysis results showed that compared to the control group, VR training significantly improves the balance function and gross motor function of children with CP, but the impact on the social function of children with CP is still controversial. Therefore, more RCTs with high quantity and quality are suggested to be performed in the future in an effort to further confirm the treatment effects of VR training on balance function, gross motor function, and the daily living ability among children with CP, as well as to offer more solid evidence for clinical trials. Therefore, we suggest carrying out more high-quality RCTs with large samples in the future to further confirm the efficacy of VR training on balance ability, gross motor function, and the daily living ability of children with CP and provide more reliable evidence for clinical practice.

Acknowledgments

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Conflicts of Interest

None declared.

Multimedia Appendix 1
Literature retrieval strategy for the PubMed database.
[PDF File (Adobe PDF File), 37 KB - games_v10i4e38972_app1.pdf]

Multimedia Appendix 2
Basic features of the included papers.
[DOCX File , 19 KB - games_v10i4e38972_app2.docx]

Multimedia Appendix 3
Risk of bias of the included papers.
[PDF File (Adobe PDF File), 180 KB - games_v10i4e38972_app3.pdf]

Multimedia Appendix 4
Begg funnel plots.
[PDF File (Adobe PDF File), 116 KB - games_v10i4e38972_app4.pdf]

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Abbreviations

BBS: Berg Balance Scale
CNKI: China National Knowledge Infrastructure
CP: cerebral palsy
GMFM: Gross Motor Function Measure Scale
MD: mean difference
PBS: Pediatric Balance Scale
PEDI: Pediatric Evaluation of Disability Inventory

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PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RCT: randomized controlled trial
SMD: standardized mean difference
VR: virtual reality
WeeFIM: The Functional Independence Measure for Children

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Review

The Effects of Virtual Reality in Maternal Delivery: Systematic Review and Meta-analysis

Nuo Xu[1*], BSc; Sijing Chen[1*], BSc; Yan Liu[1], MA; Yuewen Jing[1], BSc; Ping Gu[1], MA

School of Nursing, Nanjing Medical University, Nanjing, China

[*]these authors contributed equally

Corresponding Author:
Ping Gu, MA
School of Nursing
Nanjing Medical University
101 Longmian Avenue
Jiangning District
Nanjing, 211166
China
Phone: 86 1 358 520 5899
Email: gpapple83@163.com

Abstract

Background: Extreme labor pain has negative effects; pharmacologic analgesic modalities are effective but are accompanied by adverse effects. Virtual reality (VR) works as a distracting nonpharmacologic intervention for pain and anxiety relief; however, the effects of VR use in laboring women is unknown.

Objective: Our study aimed to determine the safety and effectiveness of VR technology during labor and delivery and investigate whether it impacts labor and patient satisfaction.

Methods: In all, 7 databases (PubMed, Embase, Web of Science, the Cochrane Library, CINAHL, China National Knowledge Infrastructure, and Wan-Fang Database) were systematically searched for randomized controlled trials of VR use in pregnancy and childbirth from the time of database construction until November 24, 2021. Two researchers extracted data and evaluated study quality using the Cochrane Risk of Bias tool 2.0. Outcome measures were labor pain, anxiety, duration, satisfaction, and adverse events. Meta-analyses were performed where possible.

Results: A total of 12 studies with 1095 participants were included, of which 1 and 11 studies were rated as “Low risk” and “Some concerns” for risk of bias, respectively. Of the 12 studies, 11 reported labor pain, 7 reported labor anxiety, and 4 reported labor duration. Meta-analysis revealed that VR use could relieve pain during labor (mean difference –1.81, 95% CI –2.04 to –1.57; $P<.001$) and the active period (standardized mean difference [SMD] –0.41, 95% CI –0.68 to –0.14; $P=.003$); reduce anxiety (SMD –1.39, 95% CI –1.99 to –0.78; $P<.001$); and improve satisfaction with delivery (relative risk 1.32, 95% CI 1.10-1.59; $P=.003$). The effects of VR on the duration of the first (SMD –1.12, 95% CI –2.38 to 0.13; $P=.08$) and second (SMD –0.22, 95% CI –0.67 to 0.24; $P=.35$) stages of labor were not statistically significant.

Conclusions: VR is safe and effective in relieving maternal labor pain and anxiety; however, due to the heterogeneity among studies conducted to date, more rigorous, large-scale, and standardized randomized controlled trials are required to provide a higher-quality evidence base for the use of VR technology in maternal labor, with the aim of improving experience and outcomes.

Trial Registration: PROSPERO CRD42021295410; https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=295410

(JMIR Serious Games 2022;10(4):e36695) doi:10.2196/36695

KEYWORDS

virtual reality technology; delivery; labor pain; anxiety; meta-analysis; systematic review; pain; pregnancy; virtual reality; maternity; labor; technology; pregnant women; review; childbirth; mental health

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Introduction

The pain of labor is the highest pain level, lasts longer than acute pain, and occurs during all 3 stages of labor (dilation of the uterus, delivery of the fetus, and delivery of the placenta) [1]. Although labor pain occurs naturally, extreme pain can lead to negative physiological changes during labor such as excessive neuroendocrine stress, maternal acidemia, and prolonged labor [2,3]. Therefore, a reasonable reduction in pain intensity and duration, within safe limits, is necessary. Although epidural analgesia (the most commonly used form of pain relief in labor) has been shown to be safe and effective in this context, it is associated with longer labor times and more surgical interventions [4]. In addition, opioids such as pethidine reduce labor pain but increase maternal drowsiness, nausea, and vomiting [5] and can even cause respiratory depression [6]. Moreover, pharmacological analgesia fails to address cognitive and emotional factors, which significantly influences pain and anxiety. Thus, the World Health Organization recommends the use of nonpharmaceutical methods of pain relief [7].

Some nonpharmacological methods of treating pain, such as music [8] and aromatherapy [9], have been developed to reduce the use of analgesic drugs, but suffer from the disadvantages of inconvenience and a precipitous learning curve [10].

Distraction is a common intervention during medical procedures and is effective in reducing pain and anxiety [11]. As an integrated distraction technology, combined with computer technology, virtual reality (VR)—creating an immersive, interactive, and imaginative 3D virtual environment—has the potential to distract people from external stimuli and enhance positive thinking [12]. VR allows user to interact with a realistic 3D virtual environment by stimulating multiple perceptions, altering the activity of the complex physiological pain modulation systems by dividing attentional tasks to reduce the level of attention to pain [12-14]. Increasing evidence supports VR as an effective distraction intervention that is a safe and effective alternative strategy for treating adults [15] and children [16], burns [17], and acute pain [18]; however, labor pain differs from other types of pain, in that it is associated with strong emotions and varies in intensity as labor progresses. Pain during uterine contractions is intermittent, whereas persistent pain is associated with generalized injuries [3]. Hence, although VR is also an effective treatment for chronic pain [15], it is not appropriate to extrapolate the findings of meta-analyses addressing the ability of VR to relieve general pain to maternal labor.

Due to the limitations of VR equipment and the number of experiments, clinical trials to date have been small-scale, and differences in experimental design have contributed to controversial findings. Thus, it is essential to evaluate the effectiveness of VR in maternal delivery, but, to our knowledge, there has been no previous systematic review that specifically focused on this issue. Further, Chinese scholars have made specific contributions to this field in recent years, and their work deserves attention.

The purpose of this review was to investigate the effectiveness and safety of using VR as a method of relieving maternal anxiety and pain. Our results will contribute to clinical practice and justify the investment in equipment used in maternity hospitals.

Methods

Overview and Registration

This systematic review conformed to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement [19] and was registered in advance in the international Prospective Register of Systematic Review database (registration number CRD42021295410).

Inclusion and Exclusion Criteria

The Population, Intervention, Comparison, Outcomes, and Study design model was used to establish the article inclusion criteria, as follows:

- Population: women aged 18-35 years, who were at >34 weeks of gestation, with a normal fetus and no pregnancy complications, able to cooperate with the study and give informed consent
- Intervention: any type of VR-based interventions, including unrestricted VR equipment and contents
- Comparison: traditional methods (such as closed observation of maternal vital signs and fetal heart rate, explanation of labor- and delivery-related precautions, nutritional guidance, and psychological care) or nonintervention
- Outcomes: primary outcomes include labor pain and anxiety; secondary outcomes include labor progress, labor satisfaction, and adverse events; no restrictions on the assessment tools
- Study design: randomized controlled trials (RCTs), case-controlled trials, and quasi-experimental studies

Studies were excluded if they were (1) reviews, animal experiments, unfinished experiments, conference papers, or study protocols; (2) not in English or Chinese; or (3) evaluated as “High risk” for risk of bias.

Search Strategy

PubMed, Embase, Web of Science, the Cochrane Library, CINAHL, China National Knowledge Infrastructure, and Wan-Fang databases were comprehensively searched for relevant literature. Studies must have been published before November 24, 2021.

Search terms were classified into 2 groups: (1) “Virtual Reality,” “Virtual Reality Exposure Therapy,” “User Computer Interface,” and “Augmented Reality”; and (2) “Pregnant Woman,” “Deliveries,” “Obstetric,” and “Parturition.” Words in each group were linked by “OR” and searched with the other group by “AND.” The databases were also searched using a combination of free words and subject word forms. Additional studies within 20 years were identified from the reference lists of the screened articles. Details of the PubMed database search strings are displayed in Textbox 1. Full details of the final search strategies for each database are available in Multimedia Appendix 1.

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Two researchers (NX and SC) screened the studies independently. First, articles were imported into Endnote X9 software (Clarivate) to remove duplicates. Titles and abstracts were then examined, followed by a careful reading of the full text and further selection according to the inclusion and exclusion criteria. Finally, the result of screenings conducted by the 2 individuals were cross-checked.

Textbox 1. PubMed search strategies.

((((((((((“Pregnant Women”[Mesh]) OR (Woman, Pregnant[Title/Abstract])) OR (Women, Pregnant[Title/Abstract])) OR (“Delivery, Obstetric”[Mesh])) OR (Obstetric Deliveries[Title/Abstract])) OR (Obstetric Delivery[Title/Abstract])) OR (“Parturition”[Mesh])) OR (Parturitions[Title/Abstract])) OR (Birth[Title/Abstract])) OR (Births[Title/Abstract])) OR (Childbirth[Title/Abstract])) OR (Childbirths[Title/Abstract])) AND ((((((((((((((((((((((((((((((((((((“Virtual Reality”[Mesh] OR “Virtual Reality Exposure Therapy”[Mesh]) OR (Virtual Reality, Educational[Title/Abstract])) OR (Educational Virtual Realities[Title/Abstract])) OR (Educational Virtual Reality[Title/Abstract])) OR (Reality, Educational Virtual[Title/Abstract])) OR (Virtual Realities, Educational[Title/Abstract])) OR (Virtual Reality, Instructional[Title/Abstract])) OR (Instructional Virtual Realities[Title/Abstract])) OR (Instructional Virtual Reality[Title/Abstract])) OR (Realities, Instructional Virtual[Title/Abstract])) OR (Reality, Instructional Virtual[Title/Abstract])) OR (Virtual Realities, Instructional[Title/Abstract])) OR (Virtual Reality Immersion Therapy[Title/Abstract])) OR (Virtual Reality Therapy[Title/Abstract])) OR (Reality Therapies, Virtual[Title/Abstract])) OR (Reality Therapy, Virtual[Title/Abstract])) OR (Therapies, Virtual Reality[Title/Abstract])) OR (Therapy, Virtual Reality[Title/Abstract])) OR (Virtual Reality Therapies[Title/Abstract])) OR (“Augmented Reality”[Mesh])) OR (Augmented Realities[Title/Abstract])) OR (Realities, Augmented[Title/Abstract])) OR (Reality, Augmented[Title/Abstract])) OR (Mixed Reality[Title/Abstract])) OR (Mixed Realities[Title/Abstract])) OR (Realities, Mixed[Title/Abstract])) OR (Reality, Mixed[Title/Abstract])) OR (“User－Computer Interface”[Mesh])) OR (Virtual System[Title/Abstract])) OR (Interface, User－Computer[Title/Abstract])) OR (Interfaces, User－Computer[Title/Abstract])) OR (User－Computer Interfaces[Title/Abstract])) OR (Interfaces, User Computer[Title/Abstract])) OR (User Computer Interfaces[Title/Abstract])) OR (Interface, User Computer[Title/Abstract])) OR (Virtual Systems[Title/Abstract])) OR (System, Virtual[Title/Abstract])) OR (Systems, Virtual[Title/Abstract])) OR (virtual environment[Title/Abstract])) OR (immersion VR[Title/Abstract])) OR (Reality, Virtual[Title/Abstract]))

Data Extraction

The basic characteristics of the included studies, including author, country, year, sample size, age, intervention, and outcome indicators were independently extracted into Microsoft Excel 2016 by 1 reviewer (NX) and checked for correctness by another (SC). Attempts were also made to contact the corresponding authors for more information about studies for which results were not reported. Any discrepancies were discussed in a consensus meeting with all the reviewers.

Quality Assessment

Evaluation was conducted independently by the 2 researchers (NX and SC), and disagreements were resolved by consensus. Study quality and risks of bias were assessed using the Cochrane Collaboration’s tool (Risk of Bias tool 2.0) for assessing risk of bias in randomized trials [20]. The Cochrane Risk of Bias tool 2.0 assesses 5 domains: bias in the randomization process, bias in deviation from established interventions, bias in outcome measurement, bias of missing ending data, and bias in selective reporting of results. Items were categorized as “Low risk,” “High risk,” or “Some concerns.” Overall risk was assessed as “Low risk” if all 5 domains were assessed as low risk and as “High risk” if any domain was assessed as high risk; all other RCTs were assessed as “Some concerns.”

Data Synthesis and Analysis

Data were analyzed using Review Manager (version 5.4; Cochrane Collaboration), and meta-analysis was performed if more than 2 studies had the same outcome and available data. The test level was set at α=.05.

For continuous outcomes, the mean difference (MD) with 95% CI was calculated when outcome measurements in all studies were made on the same scale. Standardized mean difference (SMD) was used when the studies did not yield directly comparable data [21]. Dichotomous variables were expressed as relative risk with 95% CI. The I^2 statistic was used to determine whether there was heterogeneity among studies. If the heterogeneity was acceptable (chi-square P>.10, I^2<50%), effect sizes were combined using a fixed-effects model; if the heterogeneity was large (chi-square P≤.10, I^2≥50%), subgroup analysis was performed; and when no significant clinical heterogeneity existed, a random-effects model was used [22]. A qualitative review was also performed when studies could not be included in the meta-analysis. In cases where outcome indicators were not combined for meta-analysis or only 1 study reported an outcome, a narrative approach was applied for systematic review.

Results

Selection and Characteristics of Included Studies

According to the search strategy, 1144 studies were initially retrieved, and 4 additional articles were obtained by tracking references. After the removal of duplicates, the titles and abstracts of 981 studies were screened, and 942 studies were excluded because they were unrelated or not RCTs. The full text was checked for 39 studies, of which 1 was excluded for repeated publication, 5 were uncompleted experiments, and 21 studies did not meet the inclusion criteria. Finally, 12 studies were included in our systematic review (Figure 1) [23-34].

All included studies were published between 2019 and 2021, including 4 in Chinese and 8 in English. The studies were from China [24,25,32-34], the United States [26,30], Turkey [23,29], Iran [28,31], and the Netherlands [27]. Of the 12 included studies, 11 were RCTs [23-29,31-34] and 1 was a cross-over RCT [30]. In all, 6 of the studies used VR glasses [23,24,26,29,31,33], and 3 used head-mounted VR devices [28,30,32]. The basic characteristics of the included literature are presented in Table 1.

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Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart. RCT: randomized controlled trial.

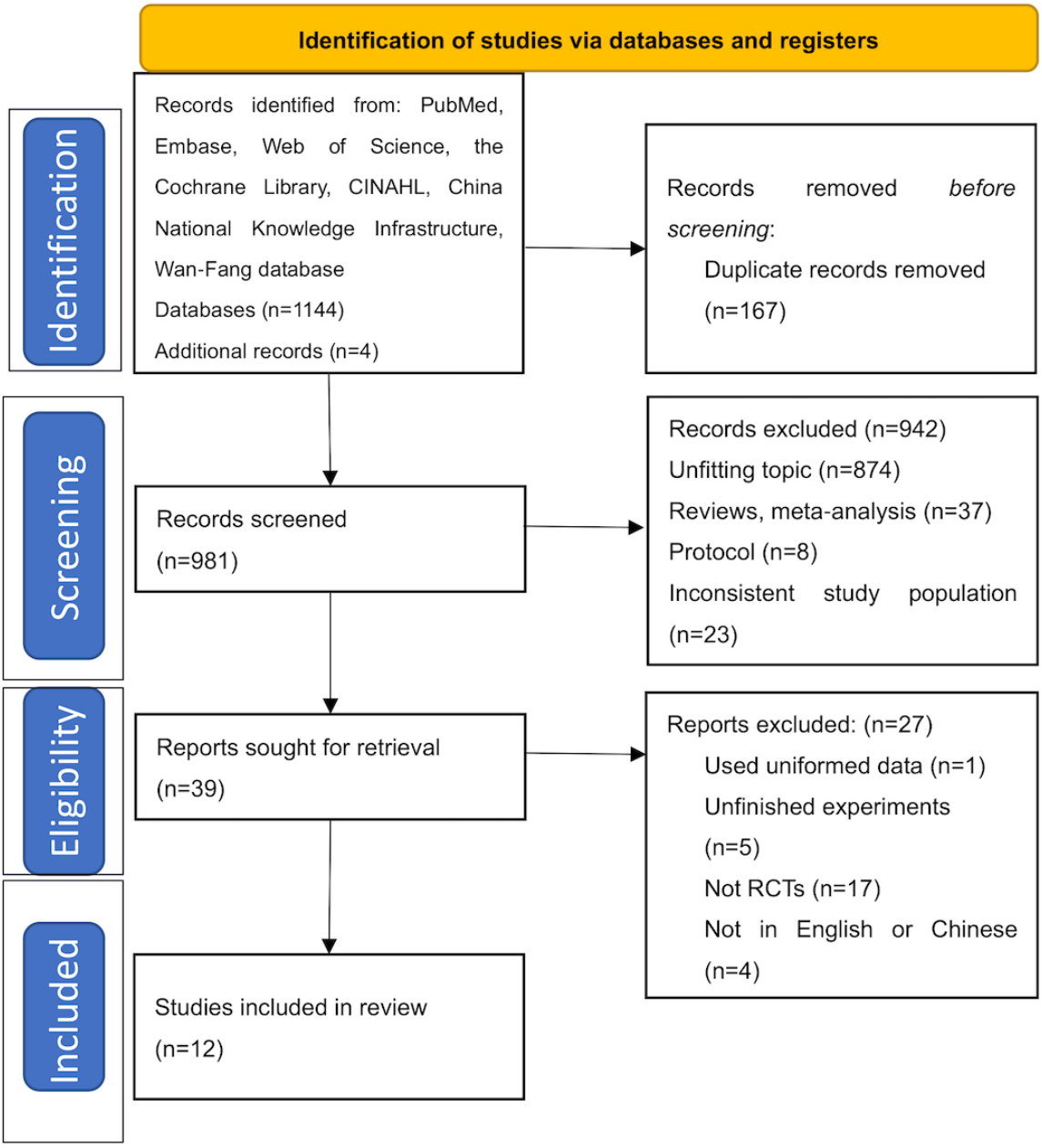

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Table 1. Characteristics of studies included in this review.

Study, year	Country	Design	Age (years), mean (SD)		Sample size, n		Content	Intervention			Outcome[a]	Instrument
			VR[b] group	Control group	VR group	Control group		Time	VR group	Control group		
Li et al [24], 2020	China	RCT[c]	24.53 (4.41)	25.6 (3.95)	35	36	Natural scenery	First stage of labor to end	R[d] + E[e] + G[f]	R	1, 2, and 4	VAS[g], VRS[h], PPI[i], SAS[j], and SDS[k]
Liang et al [34], 2020	China	RCT	27.69 (1.03)	27.47 (1.20)	30	30	Visual experience + music	First stage of labor to end	VR + R	R	1, 3, 5, and 6	VAS and EPDS[l]
Lin et al [33], 2021	China	RCT	26.24 (3.01)	27.03 (2.98)	66	48	Natural Scenery + music	Self-selected wear time, 5-60 min each time, full wear	G + music + R	R	1, 2, 3, and 4	VAS and SAS
Liu and Wan [32], 2020	China	RCT	28.72 (3.83)	27.37 (4.19)	80	80	Self-selection	VR experience 2 days after admission, 1 time per day for 2 h, worn again at the time of delivery	H[m] + R	R	1 and 2	VAS, PPI, SAS, and PRI[n]
Wu et al [25], 2020	China	RCT	28.4 (4.58)		50	49	Self-selection	30 min after epidural paroxysmal	VR + R	R	1, 2, 4, and 5	STAI[o] and NRS[p]
Akin et al [23], 2021	Turkey	RCT	27.23 (3.10)		50	50	Fetal image at 28 weeks	Intervention at delivery, mean 14.18 (SD 14.86) min	G + R	R	1, 2, and 3	VAS and PASS[q]
Ebrahimian and Rahmani Bilandi [31], 2021	Iran	RCT	24.23 (4.44)		31	31	Natural scenery + music	Use during the first and second stages of labor，20 min each time	G + R	R	3 and 4	MCSRS[r]
Frey et al [30], 2019	United States	Cross-RCT	27.9 (5.6)		27		Natural scenery + music	No more than 10 min	H + R	R	1 and 5	NRS
Gür and Apay [29], 2020	Turkey	RCT	1: 25.61 (5.14); 2: 25.89 (4.29); 3: 25.36 (4.54); 4: 27.65 (6.36)	5: 26.39 (4.32)	1: 54; 2: 55; 3: 55; 4: 55; 5: 54		1: newborn video photos + classical music; 2: video album; 3: a film introducing Turkey; 4: classical music	10 min	G + R	R	1	VAS, VRS, PPI, SAS, and SDS
Momenyan et al [28], 2021	Iran	RCT	28.41 (4.50)	30.37 (6.09)	26	26	Natural scenery + music	Performed 2 times, nearly 10 min each time	H + E + R	R	1, 2, 5, and 7	NRS and Apgar

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Study, year	Country	Design	Age (years), mean (SD)		Sample size, n		Content	Intervention			Outcome[a]	Instrument
			VR[b] group	Control group	VR group	Control group		Time	VR group	Control group		
Noben et al [27], 2019	The Netherlands	RCT	32.6 (3.9)	33.12 (4.3)	49	48	Informative video on cesarean delivery	Prenatal, unlimited time	Standard Information by VR videos	Standard Information	1, 2, and 5	VAS and TPDS[s]
Wong et al [26], 2021	United States	RCT	31.6 (5.6)	32.5 (3.6)	21	19	Natural scenery + music	30 min	G + R	R	1 and 5	PROMIS[t] global health survey

[a]Outcomes: 1=pain, 2=anxiety, 3=time of delivery, 4=satisfaction, 5=adverse effects, 6=depression, and 7=newborn endings.
[b]VR: virtual reality.
[c]RCT: randomized controlled trial.
[d]R: routine obstetric care.
[e]E: earphones.
[f]G: VR glasses.
[g]VAS: Visual Analogue Scale.
[h]VRS: Verbal Rating Scale.
[i]PPI: Present Pain Index.
[j]SAS: Self-Rating Anxiety Scale.
[k]SDS: Self-Rating Depression Scale.
[l]EPDS: Edinburgh Postnatal Depression Scale.
[m]H: Head-mounted VR device.
[n]PRI: Pain Rating Index.
[o]STAI: Spielberger Trait Anxiety Inventory.
[p]NRS: Numerical Rating Scale.
[q]PASS: Perinatal Anxiety Screening Scale.
[r]MCSRS: Mackey Childbirth Satisfaction Rating Scale.
[s]TPDS: Tilburg Pregnancy Distress Scale.
[t]PROMIS: Patient Reported Outcomes Measurement Information System.

Methodological Quality

All 12 articles had detailed inclusion and exclusion criteria and showed an acceptable risk of bias. For 6 studies [24,25,31-34], there was a possibility of bias in the randomization process, mostly because the distribution was unclear; only 1 study did not generate a random sequence [29]. Further, 11 studies were biased in deviation from established interventions [23-28,30-34], and all had low risk of bias in outcome measurement. Only 1 study did not lack outcome data [29], and 5 had unclear risk in selective reporting of results [24,25,32-34]. The risk of bias is summarized in Table 2.

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Table 2. Risks of bias for the randomized controlled trials included in this study.

Author	Year	Risk of bias assessment					Overall bias
		Randomization process	Deviations from intended interventions	Measurement of the outcome	Missing outcome data	Selection of the reported result	
Li et al [24]	2020	Some concerns	High risk	Low risk	Some concerns	Some concerns	Some concerns
Liang et al [34]	2020	Some concerns	High risk	Low risk	Some concerns	Some concerns	Some concerns
Lin et al [33]	2021	Some concerns	High risk	Low risk	Some concerns	Some concerns	Some concerns
Liu and Wan [32]	2020	Some concerns	High risk	Low risk	Some concerns	Some concerns	Some concerns
Wu et al [25]	2020	Some concerns	High risk	Low risk	Some concerns	Some concerns	Some concerns
Akin et al [23]	2021	Low risk	High risk	Low risk	Some concerns	Low risk	Some concerns
Ebrahimian and Rahmani Bilandi [31]	2021	Some concerns	High risk	Low risk	Some concerns	Low risk	Some concerns
Gür and Apay [29]	2020	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Momenyan et al [28]	2021	Low risk	High risk	Low risk	Some concerns	Low risk	Some concerns
Frey et al [30]	2019	Low risk	High risk	Low risk	Some concerns	Low risk	Some concerns
Noben et al [27]	2019	Low risk	High risk	Low risk	Some concerns	Low risk	Some concerns
Wong et al [26]	2021	Low risk	High risk	Low risk	Some concerns	Low risk	Some concerns

Effects of VR

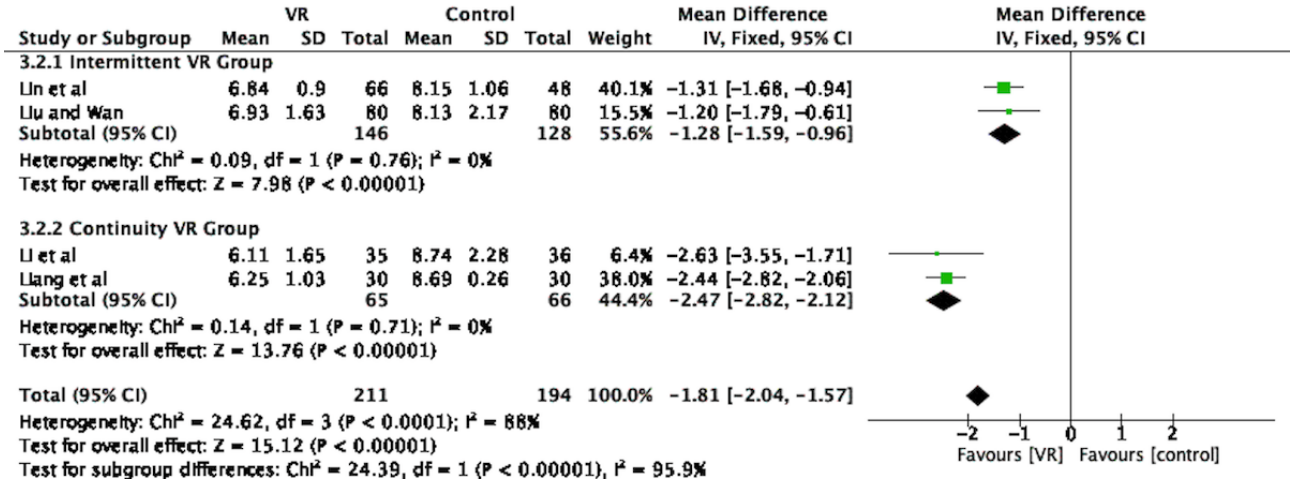
Effect of VR on Pain

In all, 4 studies explored the effect of VR on pain during childbirth [24,32-34], and another 3 explored the effect on pain reduction during the active period (when the uterus is 3-10 cm dilated) [23,26,29].

Effect of VR on Pain During Childbirth

In all, 4 studies comprising 405 patients assessed the effect of VR on maternal pain during childbirth [24,32-34]. There was significant heterogeneity among the studies (chi-square $P<.001$; $I^2=88\%$) on analysis using MD. Therefore, we divided the 4 studies into a *continuity VR group* (where VR was used from the first stage until the end of labor) [24,34] and an *intermittent VR group* (where there were interruptions in the VR) [32,33] for subgroup analysis. There was extremely high heterogeneity between the 2 groups (chi-square $P<.001$; $I^2=95.9\%$) but no heterogeneity within the intermittent (chi-square $P=.76$; $I^2=0\%$) and continuity (chi-square $P=.71$; $I^2=0\%$) VR groups. Therefore, we use a fixed-effects model for analysis. As shown in Figure 2, all differences were significant ($P<.001$).

Figure 2. Forest plot of the effect of VR on pain during childbirth. IV: inverse variance; VR: virtual reality.



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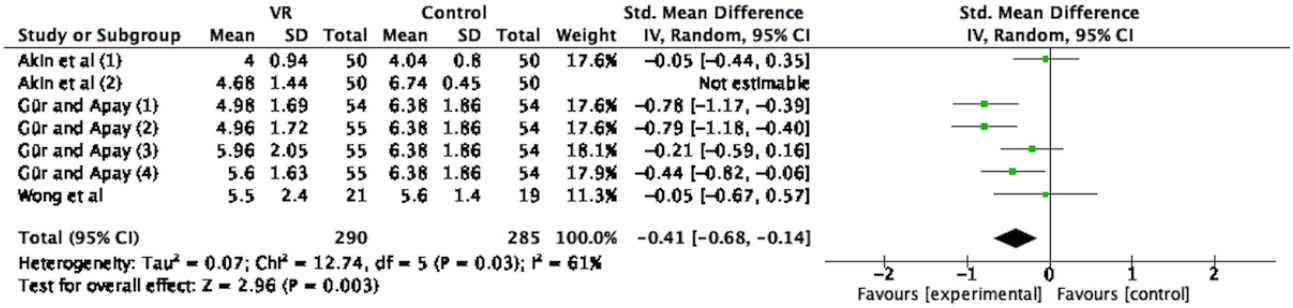
Effect of VR on Pain During the Active Period

In all, 3 studies (n=575 participants) applied VR during active labor [23,26,29]. Gür and Apay [29] divided subjects into 4 VR content groups: (1) newborn video photos and classical music, (2) video album, (3) a film introducing Turkey, and (4) classical music; each group was analyzed separately. Akin et al [23] explored the analgesic effects of VR at 4 cm ("Akin et al (1)") and 9 cm ("Akin et al (2)"), which were included as 2 experiments. SMD and random-effects models were used because of the variation in pain assessment tools (Visual Analogue Scale and Numerical Rating Scale). We found high heterogeneity among studies, likely due to differences in the duration, schedule, intensity, and type of interventions and methodological factors, and performed a sensitivity analysis. After excluding Akin et al (2), the I^2 value decreased from 87% to 61%; therefore, meta-analysis was performed on the remaining experiments and showed that VR relieved labor pain during the active period (SMD –0.41, 95% CI –0.68 to –0.14; *P*=.003; Figure 3).

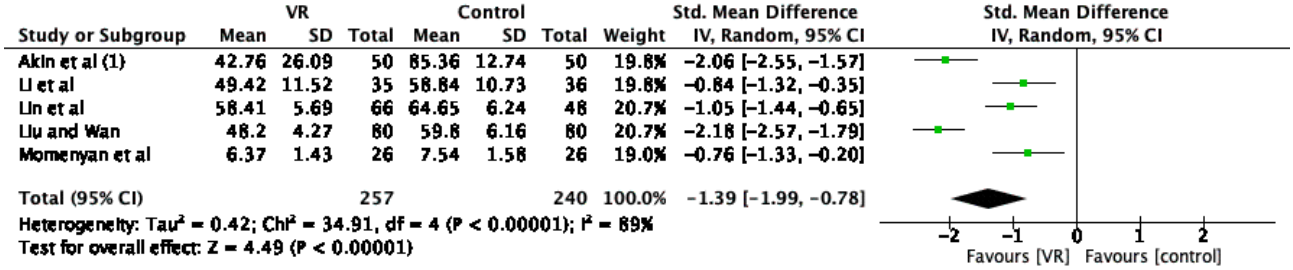
Figure 3. Forest plot for the effect of VR on pain during the active period. IV: inverse variance; VR: virtual reality.



Effect of VR on Labor Anxiety

In all, 7 studies described the effect of VR on maternal anxiety [23-25,27,28,32,33], and a meta-analysis was applied to 5 of them (n=497 participants) [23,24,28,32,33]. SMD was calculated and showed high heterogeneity among studies (chi-square *P*<.001; I^2=89%). Sensitivity analysis demonstrated that the results were stable after excluding each single study; therefore, we speculated that the high heterogeneity was likely due to differences in the duration, schedule, intensity, and type of interventions and methodological factors and applied a random-effects model. Meta-analysis showed that VR reduced maternal anxiety during delivery (SMD –1.39, 95% CI –1.99 to –0.78; *P*<.001), as shown in Figure 4.

Figure 4. Forest plot for the effect of VR on labor anxiety. IV: inverse variance; VR: virtual reality.



Effect of VR on the Process of Labor

In all, 3 studies (n=274) explored the duration of the first stage of labor [23,33,34], and 4 studies (n=336) included the second stage [23,31,33,34]. The calculation of SMD values, due to differences in measurements, and sensitivity analysis, because of the higher heterogeneity, generated stable results. The high heterogeneity may have been due to differences in measurement timing, methodology, and intervention protocols. The data presented in Figures 5 and 6 demonstrate that the effects of VR in reducing the duration of the first (SMD –1.12, 95% CI –2.38 to 0.13; *P*=.08) and second (SMD –0.22, 95% CI –0.67 to 0.24; *P*=.35) stages were not statistically significant.

Figure 5. Forest plot for the effect of VR on duration of the first stage of labor. IV: inverse variance; VR: virtual reality.

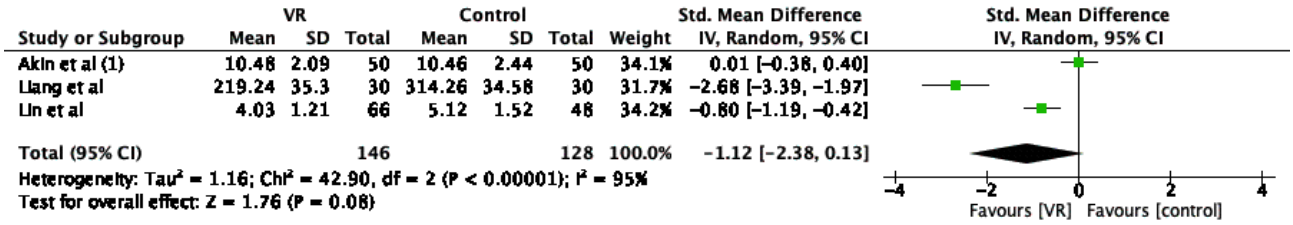


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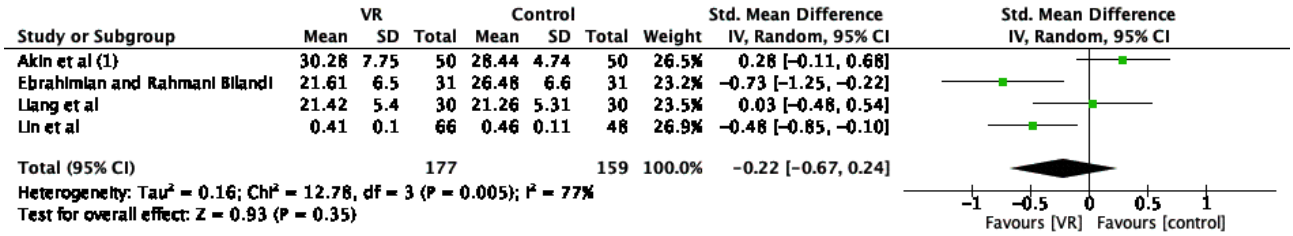
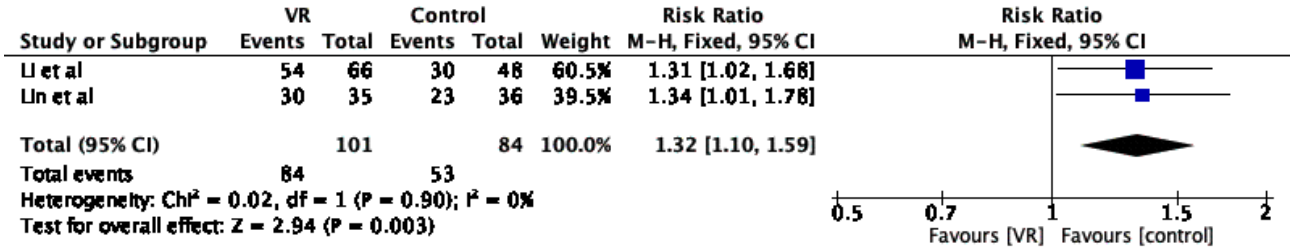
Figure 6. Forest plot for the effect of VR on duration of the second stage of labor. IV: inverse variance; VR: virtual reality.



Effect of VR on Labor Satisfaction

In all, 4 studies reported the effect of VR use on satisfaction with childbirth [24,25,31,33], and 2 (n=137) were subjected to meta-analysis [24,33], which showed significantly higher satisfaction with childbirth in the VR group (relative risk 1.32; 95% CI 1.10-1.59; *P*=.003; Figure 7). Similar results were reported by Wu et al [25] (*P*<.001) and Ebrahimian and Rahmani Bilandi [31] (*P*<.001).

Figure 7. Forest plot of the effect of VR on labor satisfaction. M-H: Mantel-Haenszel; VR: virtual reality.



Adverse Effects

In all, 6 studies reported adverse events [25-28,30,34], including nausea [25,30], vomiting [26], eye focus disorders [26,27], and dizziness [34]; however, all studies found no significant differences in the incidence of adverse events between the control and VR groups. Additionally, 2 studies reported no adverse events in 2 groups [27,28], whereas the other 6 studies did not report adverse events [23,24,29,31-33].

Discussion

Principal Findings

This study included 12 RCTs for meta-analysis and systematic review, with the aim of investigating the effectiveness and safety of VR technology during labor. We found that (1) the use of VR technology reduced maternal labor pain and anxiety, and that the effect on pain was influenced by whether exposure to VR was continuous or not; (2) there was no significant effect of the VR intervention on time to dilation of the uterine orifice in the first stage of labor or on the time to delivery of the fetus in the second stage of labor; and (3) VR used in maternal populations was safe.

VR Can Reduce the Labor Pain

The results of this review show that VR can relieve pain during childbirth. Considering the high heterogeneity among included studies, we performed a subgroup analysis, which demonstrated that the interruption of VR impacted pain reduction. It is possible that frequent interruptions, leading to less immersion in VR, diminished the distracting effect of VR for pain. We also surmised that increased maternal exposure to VR may reduce the novelty of this new technology, leading to a decrease in maternal interest in VR. This result highlights the importance of VR use at an appropriate frequency.

Regarding the active phase of labor, we performed a meta-analysis of 3 studies reporting that VR reduced pain levels, similar to the findings of other reviews of the application of VR for pain relief [27,30]. One study reported VR for epidural analgesia in labor and showed that pain relief was more pronounced in women using VR (*P*<.001) [25]. With the development of epidural techniques, the population of women undergoing such procedures in labor is likely to grow; therefore, further studies should be conducted in women undergoing epidural anesthesia to investigate its combined effect with VR and determine whether a synergistic effect can be achieved.

The VR interventions in the included studies used different contents and devices, and the intervention frequency also varied. One study found that different VR contents impacted the effect of the interventions; for example, natural landscapes could overlay with the effect of positive thinking interventions, whereas video contents, which combined visual and auditory stimuli in multiple ways, can increased the level of distraction; however, no evidence of which type of content was more effective was presented [29].

Notably, we did not identify any studies that used multidimensional tools to measure pain intensity during labor, and pain levels in the second and third stages of labor were unavailable, possibly because it was challenging to obtain accurate information under extreme conditions. Therefore, follow-up studies should focus on the timing and duration of VR use during delivery and explore the effect of different VR content on maternal delivery pain, to obtain the most effective intervention results.

VR Can Reduce the Labor Anxiety

We concluded that VR could relieve maternal anxiety during delivery, which is consistent with the findings of Eijlers et al [35], who found that applying VR could reduce anxiety in

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children; however, 1 study showed that the addition of VR for providing precesarean section information was not very effective in relieving anxiety [27], because anxiety is a persistent emotion influenced by various factors, such as lacking information, fear of pain, and worrying about the fetus [36]. Although VR can provide information visually over a short time and enhance understanding of the cesarean section, it cannot influence other sources of anxiety, such as concerns about pain and the fetus, and women undergoing planned cesarean section have a relatively longer time in which to obtain relevant information, regardless of whether they use VR. Therefore, it is essential to examine the most suitable time and appropriate populations in which to implement VR aimed at reducing maternal anxiety, to avoid the waste of resources.

VR Cannot Shorten the Labor Duration

Our review of the effect of VR on labor duration indicated that the difference in the effect of VR on the duration of the first and second stages of labor compared with the control group was not statistically significant. The labor process is influenced by a combination of psychological (anxiety, depression, fear, etc) [37] and physiological (pelvis, body mass, etc) factors [38]. VR technology only partially relieves pain and anxiety, since it involves distraction techniques [12], and thus has no statistically significant effect on labor duration. Nevertheless, some studies have shown that differences in the results were attributable to variation in the types of interventions and personal characteristics of women [33,34]; hence, further research on the effect of VR on labor duration is needed.

Satisfaction and Security of VR

According to our review, VR improved satisfaction at delivery, but most of the studies were not blinded to the subjects, which have led to bias; therefore, more RCTs blinded to subjects and investigators should be conducted in the future, to provide a basis for improving maternal satisfaction at delivery with VR.

The use of VR in maternal delivery is increasing, and the results of the review indicated that VR did not increase the incidence of adverse events during labor. In light of the small sample sizes and the lack of attention to long-term adverse effects, future studies should focus on the adverse effects of VR and lay the foundation for its standardized application in maternal delivery.

Strengths and Limitations

This is a comprehensive systematic review and meta-analysis of VR in maternal delivery. We used an exhaustive search strategy to facilitate full coverage of relevant studies and had detailed inclusion and exclusion criteria. The results of subgroup and sensitivity analyses suggested that the findings are robust. Furthermore, the studies included were conducted in ethnically diverse settings, expanding applicability.

However, this study has several limitations, due to demographic differences and clinical variations, as follows: (1) this systematic evaluation only searched studies published in Chinese and English, thus publication bias was presented due to the omission of gray studies; (2) variation in interventions and outcome indicators, as well as differences in maternal ethnicity and physical qualities among different countries, have influenced the outcomes; and (3) the low quality of the included studies and the limited sample size affected the accuracy of the results.

Explanation of Heterogeneity

Our meta-analysis detected a high degree of heterogeneity among trials. The heterogeneity across trials in the analysis of labor pain was considerable; therefore, we implemented subgroup and sensitivity analyses to further explore the sources of heterogeneity and found that, for pain during labor, the presence or absence of continuous VR intervention was an influencing factor. Second, the dispersion of the effects observed in the included trials could be due to unidentified fluctuations in labor pain, measurement method subjectivity, confusion, and the emotional stability of women in labor. For labor anxiety, differences in duration, schedule, intensity, and type of interventions and methodological factors have resulted in high heterogeneity. Differences among the observed effects on labor duration have also been due to the accuracy of determining the stage of labor and measurement methods. Additionally, other factors could have also contributed to the heterogeneity of labor pain, anxiety, and labor duration—for example, the experience of the mother in labor and the fetal condition.

Implications for Future Research and Practice

As a novel technology, VR provides considerable distraction effects, but it is still in the developmental stage, and the safety and cost-effectiveness of this approach for maternal use is debatable. It is recommended that future studies with larger sample sizes be conducted to verify the efficacy of VR. Second, based on the heterogeneity of intervention content and timing detected in this study, evidence is needed to provide fully substantiated recommendations regarding the frequency, duration, and content of VR interventions. Moreover, most of the reviewed study designs lacked theoretical support, and future studies should explore more formal models of VR intervention, to determine the optimal timing and effects of VR interventions and provide a more consistent and effective reference standard. Furthermore, the effects of VR interventions combined with epidural analgesia should be further explored, as epidural analgesia is becoming more common to reduce the abuse of analgesic drugs and their side effects. Finally, the studies did not report the long-term effects of VR use, and the measurement tools used were relatively subjective, which could have reduced their reliability. Future research could focus on (1) the construction of intervention models for VR use in labor; (2) the use of VR in combination with physiological indicators of labor, medications, etc; (3) more accurate intervention outcome measures; and (4) multicenter, large-sample, and high-quality study designs.

Conclusion

Our review confirms that VR is effective and safe as a distraction intervention for relieving labor pain and anxiety; however, research on the use of VR in maternal labor is still in its infancy, and better designed and more rigorous large-scale RCTs are needed to provide a higher-quality evidence base for the use of VR technology in maternal labor, with the aim of improving labor experience and outcomes.

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Acknowledgments

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Authors' Contributions

NX and SC contributed to conceptualization and data analysis. NX, SC, and YL contributed to the literature search and screening. PG contributed to writing—original draft preparation. NX, SC, YL, and YJ contributed to writing—review and editing.

Conflicts of Interest

None declared.

Multimedia Appendix 1
Search strategy.
[DOCX File , 17 KB - games_v10i4e36695_app1.docx]

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Abbreviations

MD: mean difference
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RCT: randomized controlled trial
SMD: standardized mean difference
VR: virtual reality

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Review

Artificial Intelligence–Driven Serious Games in Health Care: Scoping Review

Alaa Abd-alrazaq[1], PhD; Israa Abuelezz[2], MSc; Asma Hassan[2], MSc; AlHasan AlSammarraie[2], MSc; Dari Alhuwail[3,4], PhD; Sara Irshaidat[5], MD; Hashem Abu Serhan[5], MD; Arfan Ahmed[1], PhD; Sadam Alabed Alrazak[6], BSc; Mowafa Househ[2], PhD

[1]AI Center for Precision Health, Weill Cornell Medicine-Qatar, Doha, Qatar

[2]Division of Information and Computing Technology, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar

[3]Information Science Department, College of Life Sciences, Kuwait University, Kuwait, Kuwait

[4]Health Informatics Unit, Dasman Diabetes Institute, Kuwait, Kuwait

[5]Department of Pediatrics, King Hussein Cancer Center, Amman, Jordan

[6]Department of Mechanical & Industrial Engineering, Faculty of Applied Science and Engineering, University of Toronto, Toronto, ON, Canada

Corresponding Author:
Mowafa Househ, PhD
Division of Information and Computing Technology, College of Science and Engineering
Hamad Bin Khalifa University
Qatar Foundation
P.O. Box 34110, Doha Al Luqta St, Ar-Rayyan
Doha, 0000
Qatar
Phone: 974 55708549
Email: mhouseh@hbku.edu.qa

Abstract

Background: Artificial intelligence (AI)–driven serious games have been used in health care to offer a customizable and immersive experience. Summarizing the features of the current AI-driven serious games is very important to explore how they have been developed and used and their current state to plan on how to leverage them in the current and future health care needs.

Objective: This study aimed to explore the features of AI-driven serious games in health care as reported by previous research.

Methods: We conducted a scoping review to achieve the abovementioned objective. The most popular databases in the information technology and health fields (ie, MEDLINE, PsycInfo, Embase, CINAHL, IEEE Xplore, ACM Digital Library, and Google Scholar) were searched using keywords related to serious games and AI. Two reviewers independently performed the study selection process. Three reviewers independently extracted data from the included studies. A narrative approach was used for data synthesis.

Results: The search process returned 1470 records. Of these 1470 records, 46 (31.29%) met all eligibility criteria. A total of 64 different serious games were found in the included studies. Motor impairment was the most common health condition targeted by these serious games. Serious games were used for rehabilitation in most of the studies. The most common genres of serious games were role-playing games, puzzle games, and platform games. Unity was the most prominent game engine used to develop serious games. PCs were the most common platform used to play serious games. The most common algorithm used in the included studies was support vector machine. The most common purposes of AI were the detection of disease and the evaluation of user performance. The size of the data set ranged from 36 to 795,600. The most common validation techniques used in the included studies were k-fold cross-validation and training-test split validation. Accuracy was the most commonly used metric for evaluating the performance of AI models.

Conclusions: The last decade witnessed an increase in the development of AI-driven serious games for health care purposes, targeting various health conditions, and leveraging multiple AI algorithms; this rising trend is expected to continue for years to come. Although the evidence uncovered in this study shows promising applications of AI-driven serious games, larger and more rigorous, diverse, and robust studies may be needed to examine the efficacy and effectiveness of AI-driven serious games in different populations with different health conditions.

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(JMIR Serious Games 2022;10(4):e39840) doi:10.2196/39840

KEYWORDS

serious games; artificial intelligence; deep learning; machine learning; health care; digital health; eHealth; mobile phone

Introduction

Background

Since its establishment in the 21st century, video games have experienced a boom and become an ever-growing global industry [1]. In recent years, there has been a rapid increase in the accessibility and ubiquity of handheld computers and smart devices (ie, tablets, wearables, and smartphones) as well as major advances in the underlying technology and capability of commercial video game consoles [2], thereby providing a plethora of opportunities to leverage video games for many purposes. Video games used for purposes other than entertainment (eg, education, training, research, rehabilitation, and advertising) are called serious games [3].

In health care, serious games have been used for many purposes such as screening, diagnosing, education, prevention, and rehabilitation [4,5]. For example, serious games have shown promising results in improving health education [6]; acute pain management [7]; cognitive functions (eg, global cognition [8], memory [9], executive functions [10], and processing speed [11]); mental health disorders (eg, depression [12] and anxiety [13]); and functional, motor, and sensory functions [14]. Furthermore, serious games have the potential to diagnose and screen many diseases such as mild cognitive impairment [15], developmental dyslexia [16], and attention-deficit/hyperactivity disorder [17].

Serious games rely on the concept of gamification, which involves the "use of game design elements within non-game contexts" [18] through the structure, design, and methodology of games [19]. According to evidence, gamification typically relies on three elements: (1) game dynamics, including the behaviors, interactions, and experience of the player; (2) pedagogical or instructional design of the game; and (3) the mechanics (ie, procedures and rules) of the game [20]. Typically, gamification relies on the use of points, badges, leader boards, or timed performance [21,22].

Serious games exist in several formats depending on their therapeutic modality such as (1) exergames, which are video games that require physical activity to be played [23]; (2) computerized cognitive behavioral therapy games, which provide the player with structured approaches to address and recognize negative thinking and beliefs [24]; (3) cognitive training games that target improving or maintaining the player's cognitive abilities, including executive functions, memory, and learning [25]; or (4) biofeedback games that use electrical sensors attached to the player to receive information about the player's physiological state and in turn influence some of the player's body functions (eg, heart rate) [26,27].

Experts suggest that artificial intelligence (AI) is positioned to broadly reshape health care and the practice of medicine [28]. Coined by John McCarthy in a lecture at Dartmouth College in 1956 [29], AI is a branch of computer science that involves the development of methods, techniques, and systems that intelligently handle and analyze complex data sets and information. In recent years, AI models have played an increasingly central role in medical research and clinical practice through several applications including personalized screening, diagnosis, prognosis, monitoring, risk modeling, drug discovery, and prediction of response to therapy [30,31].

AI-driven serious games, which are video games combined with AI used for purposes other than entertainment, for health can offer a customizable and immersive experience that adjusts its speed and difficulty, for example, based on the player's performance [1]. Through the use of AI algorithms, serious games can monitor the performance of players in real time [32]. For example, using data mining, serious games that leverage AI can evaluate players' behaviors, mood, and personality while playing a serious game [33]. In addition, AI-driven serious games that use data mining techniques can improve players' knowledge, skills, and training progress through the analysis of the data collected playing the game [34,35].

Research Problem and Aim

Several studies have been conducted on AI-driven serious games in health care. Summarizing the features of the current AI-driven serious games is very important to explore how they have been developed and used and their current state to plan on how to leverage them in the current and future health care needs. Previous reviews did not focus on AI-driven serious games [36] and focused on a specific disease rather than health care in general [8-13]. Therefore, this review aimed to explore the features of AI-driven serious games in health care as reported by previous studies. Thus, this review focused on both AI and serious games together rather than serious games alone. Furthermore, our review is more comprehensive than other reviews, as it targeted serious games for any health condition rather than targeting a specific health condition.

Methods

Overview

To achieve the abovementioned objective, we conducted a scoping review in line with the guidelines of PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) [37]. Multimedia Appendix 1 shows the PRISMA-ScR checklist for this review. The methods used in this review are described in detail in the following subsections.

Search Strategy

Search Sources

The following databases were searched on January 12, 2022: MEDLINE (via Ovid), PsycInfo (via Ovid), Embase (via Ovid), CINAHL (via EBSCO), IEEE Xplore, ACM Digital Library, and Google Scholar. In the case of Google Scholar, only the

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first 100 publications were considered because it retrieved a massive number of publications, and we found that the results quickly lost relevance and applicability beyond the first 100 hits. To identify further studies, we screened the reference lists of the included studies and relevant reviews (ie, backward reference list checking), and we checked the studies that cited the included studies (ie, forward reference list checking) [38].

Search Terms

The search query in this review was developed by consulting 3 experts in digital health and by checking the search queries used in previous reviews within this area. The developed search query is composed of AI-related terms (eg, AI, machine learning, and deep learning) and serious games–related terms (eg, serious games and exergames). The search query used to search each of the 8 databases is shown in Multimedia Appendix 2.

Study Eligibility Criteria

In this review, we included only studies that focused on AI-driven serious games used for any purpose in health care (eg, diagnosis, rehabilitation, prognosis, quantification, screening, and forecasting). We focused only on serious games that are played on any digital platform (eg, computers, consoles, mobile phones, and handheld devices), whereas nondigital games and those used in other fields (eg, education) were excluded. We also focused on serious games provided to health consumers (patients or healthy people) rather than health care providers or caregivers. We excluded studies that provided an overview or proposal for AI-driven serious games. This review included only empirical studies written in English. Although we included peer-reviewed articles, dissertations, conference proceedings, and preprints, we excluded reviews, conference abstracts, proposals, editorials, and commentaries. We did not apply any restrictions on the year of publication, country of publication, study design, population, and outcomes.

Study Selection

The study selection process in this review consisted of three steps: (1) removing duplicates from all retrieved studies using EndNote, (2) screening titles and abstracts of the remaining publications, and (3) reading the entire text of the studies included in the previous step. In the full-text screening, we read the paper from title to conclusion in addition to the supplementary materials. Two reviewers independently performed the study selection process. Disagreements between the reviewers in the second and third steps were resolved by consulting 2 other reviewers. Cohen κ was calculated to measure the reviewer's agreement [39], and it was 0.81 for title and abstract screening and 0.86 for full-text reading.

Data Extraction

Multimedia Appendix 3 displays the data extraction form used in this review, which was pilot-tested using 5 included studies. Three reviewers independently used Microsoft Excel to extract data related to the characteristics of the included studies, serious games, and AI techniques. Any disagreement between the reviewers was resolved through discussion.

Data Synthesis

A narrative approach was used to synthesize data extracted from the included publications. Specifically, we began by describing the features of serious games used in the included studies in terms of their name, target condition, purpose, therapeutic modality, connectivity, interface, genre, types, and platform. Then, we described the features of the AI techniques used in the included studies in terms of their purposes, AI algorithms, type of data, size of the data set, type of validation, and performance. We used Microsoft Excel to manage data synthesis.

Results

Search Results

The total number of publications retrieved by searching the predefined databases was 1470 (Figure 1). We removed 181 duplicates from those publications. Checking the titles and abstracts of the remainders led to the exclusion of 1117 publications due to several reasons, as shown in Figure 1. After checking the full text of the remaining 172 publications, 129 were excluded for several reasons, as shown in Figure 1. We identified 3 additional studies using backward and forward reference list checking. Accordingly, the final number of included studies was 46 [40-85].

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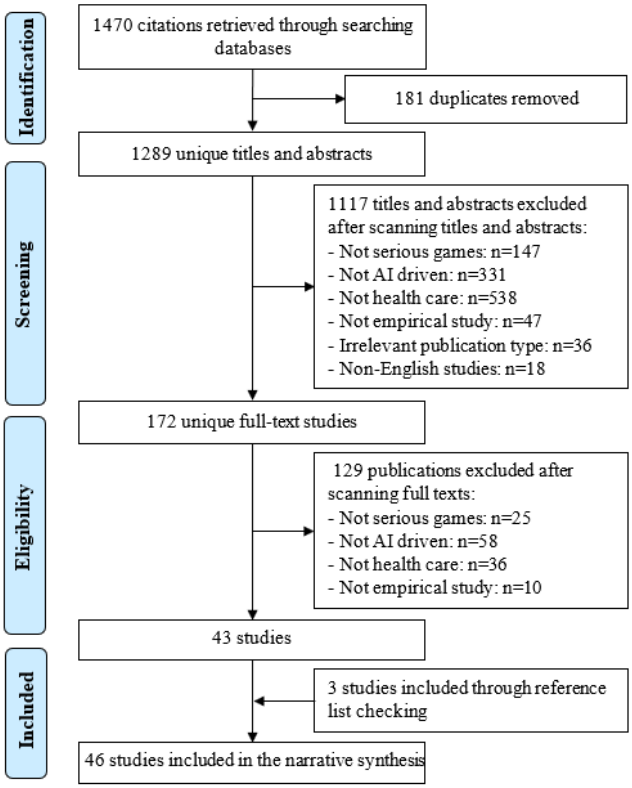
Figure 1. Flowchart of the study selection process. AI: artificial intelligence.



Characteristics of the Included Studies

The included studies were published between 2010 and 2021. The years wherein the largest number of included studies were published were 2018 (8/46, 2%) and 2019 (7/46, 15%). The included studies were conducted in 30 different countries. The countries that published the largest number of studies were the United States and Spain (5/46, 11%). The included studies were published in peer-reviewed journals (26/46, 57%) or in conference proceedings (20/46, 44%). Multimedia Appendix 4 [40-85] presents the characteristics of each included study.

Characteristics of the Serious Games

A total of 64 different serious games were found in the included studies (6 studies used >1 serious game). Of the 64 games, 16 (25%) were not given a specific name. Serious games were used for 20 health conditions. Motor impairment was the most common health condition targeted by the serious games in the included studies (18/46, 39%), followed by attention deficit hyperactivity disorder (4/46, 9%). Serious games were used for 5 purposes: rehabilitation (29/46, 63%), detection of diseases or disorders (10/46, 22%), health and wellness (5/46, 11%), education (2/46, 4%), and the prediction of players' characteristics (1/46, 2%). The therapeutic modalities in the 29 rehabilitation games were exercise (19/29, 66%), cognitive training (6/29, 21%), and biofeedback (5/29, 17%). The interface of the serious games was 2D in 19 studies, 3D in 23, and 2D and 3D in 4 studies. Serious games in the included studies could be played by a single player (45/46, 98%) or multiplayer (1/46, 2%). Serious games were connected to an internet or network connection (ie, web-based games) in 8 studies, whereas they were played on stand-alone devices (offline games) in 38 studies. There were 10 genres of serious games in the included studies, but the most common genres were role-playing games (14/46, 30%), puzzle games (11/46, 24%), platformer games (10/46, 22%), and sports games (8/46, 17%). The games were designed with a *serious* purpose from the beginning (designed serious games) in 42 studies, whereas they were usual video games that were modified to be used for a serious purpose (modified serious games) in 4 studies. The game engine used to develop serious games was reported in 38 studies. Unity was the most prominent game engine used in these studies (19/38, 50%). We identified 6 platforms used to play the serious games: PCs (30/46, 65%), mobile devices (eg, mobile phones and tablets; 10/46, 22%), virtual reality headset (4/46, 9%), treadmill (1/46, 2%), Sifteo cubes (1/46, 2%), and a single-board computer (Raspberry Pi; 1/46, 2%). The serious games were connected with other devices in 36 studies: nonwearable sensors (18/46, 39%), wearable sensors (15/46, 33%), wearable devices (7/46, 15%), web camera (7/46, 15%), robotic device (3/46, 7%), microphone (3/46, 7%), controllers (2/46, 4%), smartphone (1/46, 2%), monitor (1/46, 2%), speakers (1/46, 2%), and single-board computer (tiny PC; 1/46, 2%). Multimedia Appendix 5 [40-85] shows characteristics of the serious games in the included studies.

Characteristics of the AI Techniques

The included studies used algorithms to solve classification problems (41/46, 89%), regression problems (5/46, 11%), and clustering problems (2/46, 4%). Algorithms embedded in serious games were reported in 40 studies, whereas the remaining studies did not report the algorithms used. These studies used 27 different algorithms for serious games. The most common algorithm used in the included studies was support vector machine (14/46, 30%), followed by convolutional neural network (7/46, 15%), artificial neural networks (7/46, 15%),

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and random forest (7/46, 15%). AI algorithms in the included studies were used for 9 different purposes: detection of disease (13/46, 28%), evaluation of user performance (13/46, 28%), adaptation of difficulty level (7/46, 15%), recognition of gestures (7/46, 15%), recognition of biosignals (5/46, 11%), supporting users to play (3/46, 7%), classification of activity (2/46, 4%), recognition of voice (2/46, 4%), and prediction of user characteristics (1/46, 2%). Multimedia Appendix 6 [40-85] exhibits characteristics of AI techniques leveraged by serious games in the included studies.

The AI models in the included studies were developed using the following types of data: kinematic data (22/46, 48%), gameplay data (21/46, 46%), biosignal data (11/46, 24%), demographic data (3/46, 7%), speech data (2/46, 4%), clinical data (1/46, 2%), and laboratory data (1/46, 2%). Data used for developing the models were collected from samples ranging from 3 to 150, as reported in 36 studies. The mean sample size was approximately 36 (SD 39.3). The data set size was reported in 24 studies and ranged from 36 to 795,600, with an average of approximately 52,124 (SD 161,862.2). The AI models in the included studies were validated using 4 techniques: k-fold cross-validation (13/46, 28%), training-test split validation (13/46, 28%), leave-one-out cross-validation (7/46, 15%), and moving-window cross-validation (1/46, 2%). The performance of the AI models was evaluated in 32 studies using 11 different metrics: accuracy (26/46, 57%), sensitivity (13/46, 28%), F_1-score (9/46, 20%), precision (7/46, 15%), specificity (6/46, 13%), negative predictive value (3/46, 7%), area under the curve (3/46, 7%), root mean square error (1/46, 2%), normalized root mean square error (1/46, 2%), kappa (1/46, 2%), and Mathew correlation coefficient (1/46, 2%).

Discussion

Principal Findings

This study summarized the evidence about the features of AI-driven serious games in health care as reported by previous research. The 64 AI-driven serious games uncovered by this study targeted 20 different health conditions, were built for various purposes, and leveraged several therapeutic modalities through the use of multiple AI algorithms. The evidence uncovered in this review points to a rising trend in the use of AI-driven serious games in health care in recent years. The findings reported in this review were consistent with other recent evidence. Although a review by Frutos-Pascual and Zapirain [1] did not solely focus on AI-based serious games for health care purposes, its findings related to AI-based serious games were consistent with our findings with respect to their potential application for health care purposes, AI algorithms used, and the platforms used; there is also agreement about the need for improved testing methodologies to ensure efficacy.

Although the studies included in this review were conducted across the globe, many were conducted in 1 country. Therefore, the evidence remains scarce with respect to the compatibility of AI-driven serious games with the sociocultural practices of consumers playing them. Literature indicates that understanding a community's sociocultural practices can significantly contribute toward designing and building reliable serious games; hence, more studies in the reported countries, as well as others, are needed [86].

Most of the AI-driven serious games reported in the studies examined in this review were heavily focused on the interventional therapeutics and the detection of diseases or disorders compared with prevention (ie, health and wellness or education). Given the alarmingly rising rates of noncommunicable diseases globally (eg, diabetes and cardiovascular diseases) [87], it is imperative to invest more efforts in developing more AI-driven serious games that focus on prevention and not only treatment and therapy because of the potential of serious games in providing systematic and sustainable means of preventing or delaying the onset of such noncommunicable diseases [5,87,88].

A recent study that developed a smartphone-based serious game that teaches self-management to children aged 8 to 14 years with type 1 diabetes reported that although the developed prototype of the serious game was perceived as useful and engaging by participants, it was not adaptable to players' knowledge level and provided "information [that] was too basic for participants" [89]. This presents a great opportunity for developing AI-driven serious games that adapt to players' abilities and knowledge level [1,90,91], making them more engaging and meaningful.

The studies examined in this review that reported the game engine used to develop their AI-driven serious game predominantly used the proprietary game engine *Unity* (19/38, 50%). There is room for further development of AI-driven serious games on open-source platforms [92], which can make their development collaborative, modular, and modifiable [93]. In addition, half of the studies examined in this review required players to play the AI-driven serious game on a PC. This goes against the fast-paced adoption and ubiquity of smart devices, such as smartphones and tablets.

Although only 4 studies reported the use of virtual reality headsets, we speculate that this number will rise in the years to come with the hype of *metaverses* and availability as well as affordability of these headsets. This progression comes naturally with the increasing adoption of connected devices, including wearable and nonwearable sensors, as part of the AI-driven serious game. With this in mind, we project that AI-driven serious games will be more adaptable in an unobtrusive and affordable manner [94].

This review found that 3D serious games were slightly more common than 2D serious games, which is in line with the findings of a previous review [36]. This can be attributed to the fact that 3D games are more immersive and attractive to players. Although 4 studies used both 2D and 3D serious games, none of the serious games in these 4 studies had multimodal interfaces. More precisely, each study included >1 serious game, and the interface of each game was either 2D or 3D rather than multimodal (2D and 3D). It is worth noting that none of these studies compared the effectiveness of a 2D serious game with a 3D serious game.

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Practical and Research Implications

Practical Implications

Summarizing the features of the current AI-driven serious games helped us explore how they have been developed and used and their current state, and this will help us plan on how to leverage them in the current and future health care needs. Only 10 studies in this review used smart mobile devices (ie, tablets and smartphones). The ubiquity of smart mobile devices, coupled with their increasing capabilities, affordability, and accessibility, makes them more appealing for future applications of AI-driven serious games, and smart mobile devices are certainly more pervasive compared with personal computers and gaming consoles [8]. Estimates of global mobile devices and mobile users are reported to be 15 billion and 7.1 billion, respectively [95].

There is a need to consider the sociocultural context and player demographics when designing and developing AI-driven serious games. In addition, involving multiple stakeholders, including the targeted audience (ie, consumers or patients), is fundamental to the success of an AI-driven serious game [96,97].

Research Implications

Of the 64 studies examined in this review, 14 (22%) did not report the performance of the AI models used in the serious games. The evidence uncovered in this study demonstrates a promising potential for leveraging AI-driven serious games for health care purposes, which in turn can inform future research efforts by demonstrating the status quo of research in this domain. With the increasing adoption of AI in medical software and the development of serious games, and considering that AI models may not be fully explainable at times, it becomes imperative to rigorously test and report the performance of the models, especially in high-stakes use cases such as missing a diagnosis of disease [98].

The studies included in this review had sample sizes ranging from 3 to 150, with many of them in the lower range. More evidence and research are needed on larger sample sizes to determine the generalizability of the findings and the impact of AI-driven serious games. It is also essential to examine the efficacy and effectiveness of AI-driven serious games in different populations with different health conditions. Although many of the studies examined in this review reported the data set size used, numerous studies did not; therefore, we urge researchers to not only report the data set size but also increase it to ensure adequate performance of AI-driven serious games for health care purposes [99]. In addition, more research, including randomized control trials and systematic reviews, may be needed to examine the efficacy and effectiveness of AI-driven serious games in different populations with different health conditions.

Strengths and Limitations

Strengths

To the best of our knowledge, this is the first review of AI-driven serious games in health care. Only 1 previous review focused on serious games in health care; however, it did not focus on AI-driven serious games. Furthermore, this review can be considered the most comprehensive review in this area, given that it focused on all AI-driven serious games in health care regardless of their target health condition, therapeutic modality, game interface, number of players, connectivity, genre, type, game engine, platform, AI techniques, data types, sample size, data set size, and validation methods.

Bias resulting from the study selection was minimal in the review because the 2 reviewers independently performed the study selection process, and any disagreements between them were resolved by consulting 2 other reviewers. Furthermore, bias resulting from data extraction is not a concern in this review, as 3 reviewers independently extracted data from the included studies, and any disagreement between them was resolved through discussion. Bias resulting from missing papers is minimal, given that we sought to retrieve as many relevant studies as possible by searching the most popular databases in the information technology and health fields using a well-developed search query and by conducting backward and forward reference list checking.

Limitations

This review may have missed some relevant studies, given that we excluded proposals of AI-driven serious games (ie, a conceptual framework of a serious game), studies written in a language other than English, and studies focused on AI-driven serious games for health care providers and caregivers. Furthermore, it is likely that we missed some relevant papers, given that we did not search on Scopus and Web of Science. Therefore, it is likely that we missed other applications and features of AI-driven serious games. It was difficult to synthesize data related to the performance of AI-driven serious games for the following reasons: (1) the included studies had considerable heterogeneity in terms of game features (eg, target health condition, therapeutic modality, game interface, genre, and type), AI techniques (eg, their purpose, data type, and validation methods), and performance metrics and (2) conclusions drawn from such synthesis of games' performance may be misleading because the risk of bias in the included studies was not assessed in this review. Therefore, this review could not comment on the performance of AI-driven serious games.

Conclusions

The last decade witnessed an increase in the development of AI-driven serious games for health care purposes, and this rising trend is expected to continue for years to come. In this review, the 64 AI-driven serious games had varying data set sizes, ranging from only 36 to 795,000; these games reported targeting various health conditions, with motor impairment being the most common, and were mainly used for several therapeutic modalities, with rehabilitation being the most reported. In addition, these AI-driven serious games reported leveraging multiple AI algorithms, with support vector machines being the most used. Although the evidence uncovered in this study shows promising applications of AI-driven serious games, and considering the rise and rapid advances in AI and its pervasive use in serious games in the last decade, larger, more rigorous, diverse, and robust studies may be needed to examine the efficacy and effectiveness of AI-driven serious games in

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different populations with different health conditions. AI-driven serious games are expected to be a popular source to inspire the development and design of nearly realistic health-related and preventive interventions. Further evidence is necessary to determine their efficacy and performance.

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Conflicts of Interest

None declared.

Multimedia Appendix 1
PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) checklist.
[DOCX File , 107 KB - games_v10i4e39840_app1.docx]

Multimedia Appendix 2
Search strategy.
[DOCX File , 31 KB - games_v10i4e39840_app2.docx]

Multimedia Appendix 3
Data extraction form.
[DOCX File , 21 KB - games_v10i4e39840_app3.docx]

Multimedia Appendix 4
Characteristics of each included study.
[DOCX File , 26 KB - games_v10i4e39840_app4.docx]

Multimedia Appendix 5
Characteristics of the serious games in the included studies.
[DOCX File , 40 KB - games_v10i4e39840_app5.docx]

Multimedia Appendix 6
Characteristics of artificial intelligence techniques leveraged by serious games in the included studies.
[DOCX File , 31 KB - games_v10i4e39840_app6.docx]

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Abbreviations

AI: artificial intelligence
PRISMA-ScR: Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews

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Review

Older Adults' Experiences and Perceptions of Immersive Virtual Reality: Systematic Review and Thematic Synthesis

David Healy[1], MSc; Aisling Flynn[2], BSc; Owen Conlan[3], PhD; Jenny McSharry[1], PhD; Jane Walsh[1], PhD

[1]School of Psychology, University of Galway, Galway, Ireland

[2]School of Nursing and Midwifery, University of Galway, Galway, Ireland

[3]School of Computer Science and Statistics, Trinity College Dublin, Dublin, Ireland

Corresponding Author:
David Healy, MSc
School of Psychology
University of Galway
University Rd
Galway, H91 TK33
Ireland
Phone: 353 863014265
Email: d.healy24@nuigalway.ie

Abstract

Background: Immersive virtual reality (IVR) can be defined as a fully computer-generated environment shown on a head-mounted display. Existing research suggests that key features of IVR can assist older adults in their everyday lives, providing opportunities for health promotion and tackling social isolation and loneliness. There has been a surge in qualitative studies exploring older adults' experiences and perceptions of IVR. However, there has been no systematic synthesis of these studies to inform the design of new, more accessible IVR technologies.

Objective: This study aimed to systematically review and synthesize qualitative studies exploring older adults' experiences and perceptions of IVR.

Methods: A systematic review and thematic synthesis were conducted following the ENTREQ (Enhancing Transparency in Reporting the Synthesis of Qualitative Research) guidelines. In total, 2 reviewers completed title and abstract screening, full-text screening, data extraction, and quality appraisal. Thematic synthesis is derived from the qualitative method, thematic analysis. It involves 3 key steps: initial coding and grouping of these codes, the formation of descriptive themes from these codes, and going beyond these data to form analytical themes. Confidence in the evidence was assessed using the Grading of Recommendations Assessment, Development, and Evaluation-Confidence in the Evidence from Reviews of Qualitative Research approach.

Results: Overall, 13 studies were included in the final synthesis, including 224 participants across 9 countries and 5 continents. Confidence in the evidence ranged from high to moderate. Three descriptive themes were generated: practical aspects of IVR use, experiencing unique features of IVR, and perceptions of IVR. The findings from the descriptive themes suggested that there are several improvements that need to be made to existing IVR devices to facilitate older adults' use of this technology. However, older adults' responses to IVR were generally positive. Three analytical themes were generated: tolerating the bad to experience the good, buying in to IVR (don't judge a book by its cover), and "it proves to me I can do it." The analytical themes illustrated that older adults were willing to tolerate discomforts that accompany existing IVR technologies to experience features such as immersive social networking. There was a discrepancy between older adults' perceptions of IVR before use—which were generally negative—and after use—which were generally positive—and IVR provided a platform for older adults to access certain activities and environments more easily than in the real world because of limitations caused by aging.

Conclusions: This review offers insights into older adults' experiences and perceptions of IVR and suggests how a few improvements to its existing hardware and software as well as how it is first presented could offer new opportunities for older adults to take part in meaningful activities tailored to their needs and preferences.

Trial Registration: PROSPERO CRD42020200774; https://tinyurl.com/8f48w2vt

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KEYWORDS

older adults; virtual reality; immersive virtual reality; aging; systematic review; qualitative evidence synthesis; thematic synthesis

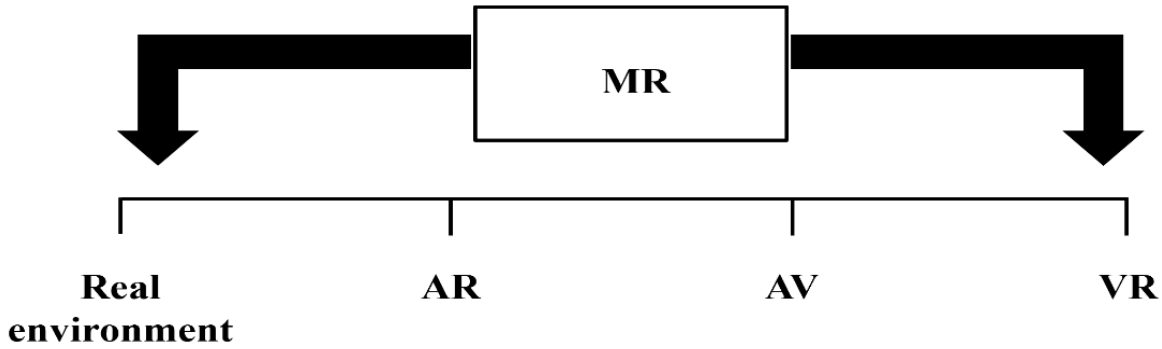
Introduction

Rationale

On the basis of projections reported by the World Health Organization (WHO), the number of people aged >60 years will rise from 900 million (12% of the global population) in 2015 to 2 billion (20% of the global population) by 2050 [1]. With the number of people living longer increasing, a new set of challenges arises that needs to be overcome to support the population into old age. The natural decline in physical and mental capabilities as we age poses a serious threat to the quality of life of older adults—particularly when society is not currently equipped to effectively cater to these declines in a way that supports healthy aging [2].

The current digital age offers new opportunities to support healthy aging in older populations. A digital technology that has evolved rapidly in the past 10 years is immersive virtual reality (IVR) [3]. On the basis of the reality-virtuality continuum by Milgram et al [4] (Figure 1), IVR is defined as fully computer-generated environments that are shown on a head-mounted display (HMD). IVR sits on the virtuality end of the reality-virtuality continuum. The reality end of the continuum refers to the real environment in which no computer-generated content is overlaid. Between these 2 ends are augmented reality–based displays, where digital information is overlaid onto the real environment through devices such as see-through HMDs, mobile phones, and computer monitors. Slater and Sanchez-Vives [5] described the technical goal of IVR as its ability to "replace real sense perceptions by the computer-generated ones," simulating what is known as presence and immersion. Presence refers to the feeling of being present in a place (ie, in a virtual environment), and immersion refers to the level of intensity with which one feels that they are present in that place afforded to them by the technological capabilities of the IVR device [5]. Closely linked to presence and immersion are colocation and copresence, which refer to networked virtual environments that enable IVR participants to interact with others (colocation) and feel as if they are there with them in the virtual environment (copresence) [6]. IVR participants are represented in IVR by avatars, which can be described as "human-like machines" that represent the participant in the virtual environment [7]. This representation is known as embodiment, which refers "...to the process of replacing a person's body by a virtual one" [5].

Figure 1. Reality virtuality continuum (adapted from Milgram et al [4] with permission from the authors). AR: augmented reality; AV: augmented virtuality; MR: mixed reality; VR: virtual reality.



In their scoping review, Hughes et al [8] discussed how features of IVR such as presence and immersion can assist older adults in their everyday lives, providing opportunities for health promotion and tackling social isolation and loneliness. IVR offers older adults the opportunity to take part in physical activities from their own home that would otherwise need to be facilitated outdoors (eg, virtual cycling in nature [9]). The comfort and convenience of activities such as these being facilitated in a more accessible environment can offer greater motivation for older adults to adhere to health-promoting activities such as physical exercise [8]. Through the incorporation of avatars into networked virtual environments, IVR also offers older adults the opportunity to connect with others in a more meaningful way compared with other communication mediums [6] where meeting in person may not be possible—a reality forced upon many of us during the COVID-19 pandemic [7]. These features align closely with the goals of the WHO for healthy aging [1], particularly with regard to age-friendly practice [1,10]. Age-friendly practice emphasizes the importance of supporting older adults in maintaining a fulfilling and meaningful life into old age through supportive infrastructures in the environment and society. IVR provides an entirely new set of virtual infrastructures that support an environment in which older adults can connect with family, friends, and other members of society [5].

With the emergence of new, high-quality IVR technologies that are now commercially available in higher-income countries, researchers have begun to examine older adults' experiences and perceptions of IVR. A number of recently published systematic reviews and systematic review protocols have aimed to synthesize the quantitative literature on this topic [11-13], focusing primarily on IVR's effectiveness, efficacy, and feasibility in various clinical populations. In recent years, we have also seen an increase in qualitative studies examining older adults' experiences and perceptions of IVR [14-16]. However, to our knowledge, there has been no systematic synthesis of these studies to inform the design of new, more accessible IVR devices for older adults.

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In digital technology development and design, qualitative feedback from end users can be invaluable. It provides developers and other informants with rich information to work with when designing digital technology content, with particular utility in identifying various barriers to and facilitators of using a technology [17]. It also offers the opportunity to explore more deeply whether the end user finds a technology acceptable—which is now considered a key factor in determining whether a technology will be adopted and used by the intended user [18]. When defining technology acceptance, it is important to acknowledge the temporal nature of the term [18], with acceptability defined as one's perception of a technology before use [19], acceptance defined as one's perception of the technology after initial use [19], and adoption defined as a multiphase process starting with "deciding to adopt (selecting, purchasing or committing to use it) and then achieving persistent use" [20].

Using the Sample, Phenomenon of Interest, Study Design, Evaluation, and Research Type tool (Textbox 1) [21], the following research questions were formulated to guide the review and synthesis of the existing literature: (1) What are older adults' experiences and perceptions of IVR? (2) What are the barriers to and facilitators of older adults' use of IVR? (3) Do older adults find IVR acceptable?

Textbox 1. Sample, Phenomenon of Interest, Study Design, Evaluation, and Research Type (SPIDER) tool for defining research questions and search terms.

SPIDER constructs and description

- Sample: in this review, the sample of interest was older adults aged ≥60 years.
- Phenomenon of interest: the phenomenon of interest in this case was older adults' experiences and perceptions of immersive virtual reality (IVR). The experience of presence, described by Slater and Sanchez-Vives [5] as the feeling of being present in the virtual world with the belief that the events occurring there are really happening, is a key characteristic of IVR that enables the enhancement of the virtual experience. As one removes the sensory substitutions that enable this sense of presence, such as a head-mounted display and haptic devices, the experience changes drastically for the user, making it more challenging to link the qualitative experience. Therefore, as each of the technologies across the reality-virtuality spectrum provide different experiences for the user, it was decided that adhering to the definition of IVR by Milgram et al [4] would provide a more meaningful and translatable qualitative synthesis.
- Design: the study designs searched for in this review used qualitative research methods such as focus groups and semistructured interviews.
- Evaluation: as this review was interested in individuals' experiences of interacting with an object, terms such as "acceptability" and "usability" were included to identify studies.
- Research type: qualitative and mixed methods studies were searched for.

Objectives

The objective of this study was to systematically review and synthesize qualitative studies exploring older adults' experiences and perceptions of IVR.

Methods

A protocol detailing the background, rationale, and methods of this systematic review has already been published [22]. This systematic review and thematic synthesis were completed following the ENTREQ (Enhancing Transparency in Reporting the Synthesis of Qualitative Research) guidelines [23].

Search Strategy

A detailed search strategy was developed to identify studies relevant to the review questions (Multimedia Appendix 1). After consulting with a librarian at the university and examining databases used in previous reviews with similar research questions to this review [11,13,24-30], 3 databases were selected to run the search in: Embase, Compendex, and Scopus. These databases were selected as they covered key fields relevant to this review, including computer science, engineering, human-computer interaction, psychology, and health and social sciences. The search strategy was developed for Embase and adapted where necessary for the other databases. The search terms were informed by previous systematic review search strategies with similar research questions [13,24-30] as well as input from the review team. Relevant keywords and phrases were used in each database, including *older adults*, *virtual reality*, *perceptions*, and *experiences*. The search terms were organized into relevant categories using the Sample, Phenomenon of Interest, Study Design, Evaluation, and Research Type tool [21] and then combined into a single search strategy. In some databases, certain categories were omitted from the final search strategy to broaden the scope of studies captured by the search. To ensure that the replicability of these searches is possible, these omissions can be examined in the link provided in Multimedia Appendix 1. Owing to the dramatic evolution of IVR equipment in recent years [3], databases were searched for relevant studies published in English from January 2012 to July 2020—an approach also taken in a recently published systematic review exploring IVR [13].

Inclusion and Exclusion Criteria

Studies were included if they examined older adults' experiences and perceptions of IVR. As there is no generally accepted definition of older adults, we included those studies in which the mean age of the study sample was ≥60 years as this is a commonly used cutoff in aging research [31]. Only studies in which complete visual immersion was facilitated through the use of an HMD were included. Studies were included if a qualitative method was used for both data collection and analysis, they were peer-reviewed publications, and they were written in English.

Older adults with a diagnosed neurodegenerative disorder were excluded as there is evidence that their experiences with virtual

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reality—as well as the application of virtual reality in this cohort—differ considerably from neurotypical individuals' experiences [32]. Reviews, conference abstracts, opinion pieces, gray literature, and editorials were excluded.

Screening and Data Extraction

The initial search was conducted by one reviewer (DH). The screening phase of this review consisted of title and abstract screening, full-text screening, and forward and backward citation searching of the included full-text articles. Title, abstract, and full-text screening was completed for studies identified through forward and backward citation searching.

Titles and abstracts were extracted from the chosen databases and combined in EndNote X9 (Clarivate). Duplicates were removed using the Remove Duplicates function in EndNote X9. Records were manually screened for remaining duplicates in EndNote X9. Title and abstract screening was conducted by one reviewer (DH) using the Rayyan (Rayyan Systems, Inc) data screening tool [33]. A random sample of 20% (491/2455) was also screened by a second reviewer (AF). A Cohen κ statistic of 0.96 was calculated, indicating almost perfect agreement between reviewers [34]. Where disagreements arose, unresolved cases were discussed with a third reviewer (JW, OC, or JMS depending on the expertise required) until an agreement was reached. Full-text screening was completed by 2 independent reviewers (DH and AF). Where disagreements arose, unresolved cases were discussed with a third reviewer (JW, OC, or JMS depending on the expertise required). Forward and backward citation searching was completed for all the studies included after full-text screening. This search was conducted by DH. Title, abstract, and full-text screening of the studies identified through forward and backward citation searching was completed by 2 reviewers (DH and AF).

Data extraction was completed following a data extraction protocol developed by DH (Multimedia Appendix 2), with feedback from the rest of the review team. In total, 2 reviewers performed the data extraction (DH and AF) using a prespecified data extraction checklist [22]. The extracted data were organized and analyzed using the NVivo software (QSR International) [35].

Quality Assessment

The Critical Appraisal Skills Programme tool [36] for qualitative research was used to appraise the quality of individual studies. No studies were excluded based on this appraisal. However, the outcomes of the appraisal were noted for each study and used to inform the synthesis of findings. The Grading of Recommendations Assessment, Development, and Evaluation-Confidence in the Evidence from Reviews of Qualitative Research (GRADE-CERQual) approach [37] was used to assess the confidence that can be attributed to the evidence informing each individual review finding, with ratings of high, moderate, or low confidence being attributed to each finding.

Thematic Synthesis

A thematic synthesis [38] was conducted to synthesize the data extracted from the included studies. Thematic synthesis is derived from the qualitative method, thematic analysis [39-41]. Several interpretations of thematic analysis are cited by authors when discussing how they conceptualized thematic synthesis. Thomas and Harden [38] state that their approach "concurs with [Boyatzis's] conceptualization of thematic analysis"—where thematic analysis is not defined as a qualitative method in its own right but as "...a process that can be used with most, if not all, qualitative methods..." [41]. This concurrence is due to the fact that their approach to thematic synthesis incorporates multiple other established methods as well as techniques commonly described as thematic analysis [38].

For this synthesis, the interpretation of thematic analysis (or reflexive thematic analysis [42]) by Braun and Clarke [39] informed the synthesis approach, structured within the stages of the thematic synthesis by Thomas and Harden [38]: (1) line-by-line coding of the extracted data from each included study, (2) grouping of these codes to form descriptive themes that remain close to the data presented in each included study, and (3) going beyond these data to create new interpretations or theories (analytical themes) of the combined studies. These themes were then formed into a coherent narrative and reported in the Results section. A table detailing exactly how the steps by Braun and Clarke [39] were mapped onto the stages of thematic synthesis can be found in Multimedia Appendix 3.

Reflexivity

Qualitative research is generally considered a subjective process [43], meaning that it is essential to be reflexive throughout it. Authors must reflect on how their perspectives, experiences, and worldviews influence the qualitative process. In total, 3 authors have backgrounds in health psychology (DH, JW, and JMS), two of whom are experts in their fields (JW and JMS); one author is a qualified occupational therapist and human-computer interaction researcher (AF); and one author is an expert in computer science (OC). During the review process, the authors' preconceptions about the topics being discussed were considered when making key decisions relating to the review, analysis, and write-up. The lead author kept a reflexive journal of the review, analysis, and write-up processes as a record of the critical evaluation of the authors' influence on the study.

Protocol Deviations

Owing to the amount and depth of data analyzed in this review, the analysis predominantly focused on only one of the primary review questions: *what are older adults' experiences and perceptions of immersive virtual reality?* The 2 other review questions were formed into secondary review questions—*what are the barriers and facilitators to older adults' use of immersive virtual reality?* and *do older adults find immersive virtual reality acceptable?*—and were addressed to a lesser extent. This deviation is in line with the assertion by Braun and Clarke [43] that qualitative research questions can evolve as the research study progresses as a greater understanding of the data being analyzed is formed.

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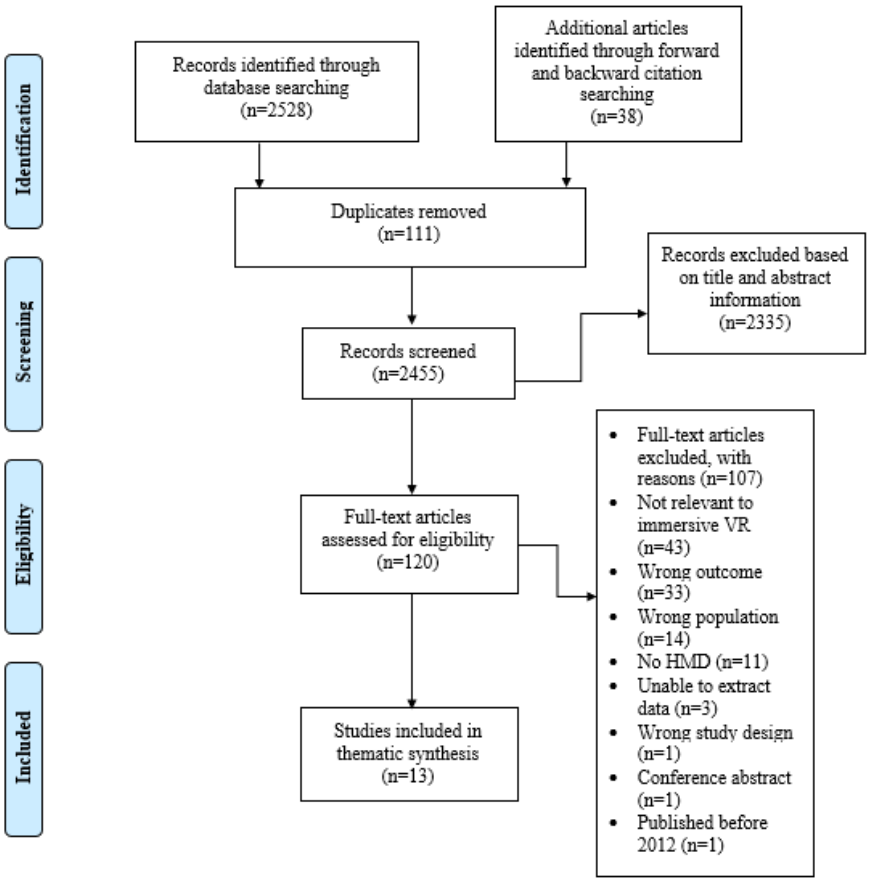
Results

Search Results

In total, 2528 records were identified through database searching. An additional 38 records were identified through forward and backward citation searching. Of the total 2566 records, 111 (4.33%) duplicates were removed, leaving 2455 (95.67%) records to be screened. A total of 95.11% (2335/2455) of records were excluded based on title and abstract information, leaving 120 articles to be assessed during full-text screening. Upon completion of the screening process, 13 studies were included in the final synthesis. This process has been illustrated as a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram in Figure 2.

Figure 2. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram. HMD: head-mounted display; VR: virtual reality.



Study Characteristics

A total of 13 studies were included [9,14-16,44-52]. In total, 77% (10/13) of the studies explicitly reported conducting some form of qualitative data collection procedure [15,16,44-46,48-52], which included focus groups [44,50], exploratory workshops [14], video recordings [9], and self-reported qualitative data [47]. A total of 224 participants were included across the 13 studies. In the 77% (10/13) of studies [9,14-16,44,46-50] that reported participants' gender, 73 (37.62%) participants were men and 121 (62.37%) were women. The participant age range across the 13 studies was 48 to 99 years. Participants lived across 9 different countries (Australia [14,15,45], China [16,47], United States [44,50], Denmark [9], Northern Ireland [46], Brazil [48], England [49], Taiwan [52], and Thailand [51]) and 5 different continents (Australia [14,15,45], Asia [16,47,51,52], North America [44,50], South America [48], and Europe [9,46,49]).

Of the 10 studies that reported the participants' place of residence, participants from 5 (50%) studies identified as community-dwelling adults [14,16,44,47,50], and participants from 5 (50%) studies reported living in some form of residential aged-care facility [9,15,45,46,50]. Although it could be assumed that almost all the participants were retired or not working as many lived in residential aged-care facilities, only 31% (4/13) of the studies explicitly reported their participants being retired [9,15,45,50]. In total, 85% (11/13) of the studies reported their recruitment strategy, which included recruiting through community organizations and day centers [16,45,46,49,50,52], posting flyers in public places [14,44], and recruiting through a residential aged-care facility [15] and a physical therapist [9], as well as 8% (1/13) of the studies that described recruiting participants sequentially [48]. Of the 5 studies that reported participants' mental status, 1 (20%) provided a detailed report on 2 of its participants, with one participant described as being depressed, self-isolating, having a history of behavioral issues, and having mild cognitive impairment and the other participant described as also having mild cognitive impairment [15]. Participants from 23% (3/13) of the studies were generally described as cognitively healthy [9,46,48]. It was reported in

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8% (1/13) of the studies that participants were not screened for cognitive impairment, but 3 participants disclosed during focus groups that they had "some dementia" [50]. In total, 46% (6/13) of the studies reported the health status of their participants, with 17% (1/6) reporting some participants being wheelchair users [15], 17% (1/6) having some participants who used walking aids and had a high risk of falling [46], 50% (3/6) reporting participants as having fair health or sufficient health to take part in the activity [9,44,48], and 17% (1/6) reporting cases of arthritis [45].

A total of 54% (7/13) of the studies reported the location where the study took place, including a day center [46,49]; a residential aged-care facility [15]; a community activity center [16]; a laboratory setting [44]; a physical therapy clinic [9]; and a room that had a flat, even floor surface with a trackable area of 2.4×2.4 m [45]. In total, 69% (9/13) of the studies reported participants' previous technology experience or proficiency [9,14,15,44,45,48-50,52], with experience and proficiency across the studies ranging from high to low.

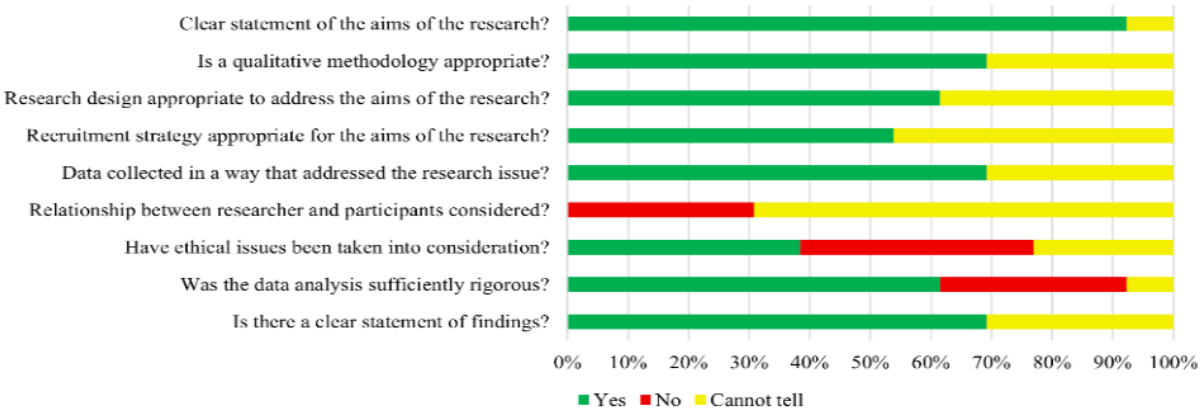
There was also a range of activities in which participants from each study took part during their IVR experience. The characteristics of these activities are included in this section to further contextualize the experiences referred to in the descriptive and analytical themes reported in the following sections. The specific applications through which the participants completed these activities can be found in Multimedia Appendix 4 [9,14-16,44-54]. The types of activities older adults engaged in across these studies included travel and exploration [15,16,44,45,47,50,51], social connection [14,15,44,48,50,52], entertainment [15,47,49,50], exercise [9,46,48], education [14,47,50], and reminiscence [44,48-50]. Descriptions of these activities and supporting author and participant quotes can be found in Multimedia Appendix 5 [9,14-16,44-52].

Quality Appraisal

A summary of the methodological quality assessment of the included studies using the Critical Appraisal Skills Programme tool is shown in Figure 3, with full details in Multimedia Appendix 6 [9,14-16,38,39,44-52]. All but 8% (1/13) of the studies [49] had a clear statement of their aims. It was unclear whether the qualitative methodology was appropriate in 31% (4/13) of the studies [9,47,51,52] and whether the research design was appropriate in 38% (5/13) of the studies [9,47,49,51,52]. It was unclear whether the recruitment strategy was appropriate in 46% (6/13) of the studies [45,47-49,51,52] and whether the data were collected in a way that addressed the research issue in 31% (4/13) of the studies [45,47,51,52]. The main reason for this uncertainty was that the authors did not clearly justify the rationale for their methodology, research design, recruitment strategy, or data collection technique.

In 31% (4/13) of the studies [47,49,51,52], there was no consideration of the researchers' relationship with the participant, and it was uncertain in the remaining studies [9,14-16,44-46,48,50]. No ethical concerns were considered in 38% (5/13) of the studies [9,45,47,51,52], and data analysis was considered not sufficiently rigorous in 31% (4/13) of the studies [46,47,51,52].

Figure 3. Methodological quality assessment of included studies.



Confidence in the Evidence

Confidence in the evidence was assessed using the GRADE-CERQual [37] tool and ranged from high to moderate (Multimedia Appendix 7 [9,14-16,44-52]). There was consistency in the findings across countries, continents, and settings. Ratings of moderate certainty were mostly due to methodological limitations and adequacy. The most common methodological limitation was the lack of reflexivity regarding the relationship between the researchers and participants. The main concern regarding adequacy was the lack of rich data informing a number of the findings.

Overview of Thematic Synthesis

Three descriptive themes were generated that were related to older adults' experiences and perceptions of IVR: (1) practical aspects of IVR use, (2) experiencing unique features of IVR, and (3) perceptions of IVR. Textboxes 2 to 4 include illustrative quotes for each descriptive theme and its respective subthemes. Author quotes are italicized to distinguish them from quotes provided by research participants in each of the studies.

Three analytical themes were then formulated by interpreting key patterns present across the descriptive themes, generating new meaning from the synthesis: (1) tolerating the bad to experience the good, (2) buying into IVR (don't judge a book by its cover), and (3) "it proves to me I can do it."

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Textbox 2. Illustrative quotes for the descriptive theme of practical aspects of immersive virtual reality (IVR) use and its subthemes.

Interacting with IVR hardware and software

- "I would never wear anything that heavy to watch something." [50]
- "But I think this device is worn on the head, and there is something on the head that always makes me feel uncomfortable." [16]
- "with the headset the movement was throwing me off a bit I think, and making me feel sort of disorientated and dizzy." [46]
- "...[the HMD is] in need of improvement in ways such as accommodating larger glasses..." [50]
- "*Some indicated that the smoothness of the plastic made it difficult to press track and menu buttons with confidence.*" [45]
- "*Participants stated that whilst at first they could remember buttons they forgot during the main exercise and became frustrated because there were too many option [buttons] to choose from.*" [45]
- "*They [participants] did not report having many problems and even enjoyed this aspect [handheld controllers], as it added a sense of control.*" [44]
- "*Some [participants] found that background noise and conversations from other people in the room was distracting and disconcerting.*" [45]
- "*Many felt VR is promising, but in need of improvement in ways such as '*...increasing the crispness of images.'" [50]
- "In terms of image, in terms of quality, in terms of sound, in terms of perception, virtual reality is much better." [48]
- "There is so much to watch here!...It's amazing to look at the birds." [9]
- "She [virtual avatar] asked me if I wanted to dance...well...she's...invited me to dance and asked me to be careful with the chair." [48]

Risks and requirements of IVR

- "I would prefer to have somebody [...] Well for instance you saying to me 'Sit down, the chair is right behind you.' You know it is going to be there, but still, it gives you the confidence to know that somebody is actually telling you that." [46]
- "*Because of physical problems, such as weak vision, high blood pressure, and motion sickness, some elderly people reported to feel dizzy and other discomfort. At the same time, the equipment is still relatively cumbersome, and it may be uncomfortable to wear on the head.*" [16]
- "I can't see well. This is a place to pay the homage [sic] but I can't see the prayers. Can I wear glasses?" [51]
- "It's difficult for older people to turn...you really have to turn your whole self." [50]
- "Waving swords is too intense for me. Maybe something gentler, you know, like picking apples." [47]
- "As you get older, you're less mobile and you can see...you can bring people together in [social VR]...you'd [feel] 'I'm not going to get on the bus...but let's get together in [social VR].'" [14]
- "Because of my age, I can't visit some attractive places. [Even though] I want to, I don't dare to go and my children will be worried about it. [But] If you watch it [VR], it is a kind of enjoyment as well as filling in an inner gap for yourself." [16]
- "if I don't do something consistently, I have to go back and write it down and have the directions written." [50]
- "I found the system, once it was explained to me, it was quite simple to use. It was quite easy." [46]

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Textbox 3. Illustrative quotes for the descriptive theme of experiencing unique features of immersive virtual reality (IVR) and its subthemes.

Presence and immersion

- "*At the conclusion of his first session using the underwater discovery game 'Ocean Rift,' Neville commented that* 'it really feels like you are underwater.'" [15]
- "There was simply...more...You completely get the sensation what you were actually driving inside the landscape...You are out in the middle of it all! Can you believe it?" [9]
- "I also like it, the feeling of being there." [16]
- "Visualization is better, the participation, you're more inside than on the cell phone, as if I were in the living room of my house." [48]
- "[virtual reality] removes you from your thoughts and your worries and, and you don't hear the phone ring and you...don't have any distractions at all..." [50]
- "It was just like being on a roller coaster. It was really good. Every bit, every bump you can actually feel." [49]
- "It's supposed to be a circus, I guess, but...I didn't feel it was a circus." [50]
- "to get any real benefit out of [social VR], you'd have to believe that [the avatar represented] that person. They would have to show some sort of emotion...there wasn't the interaction." [14]
- "Wow, 100%, music from my time, it all helped!...I saw my daughter there dancing on the rug, as if I were in my living room." [48]
- "Then when I went, I went into the dance, I started shaking my head so I do not know if...I felt a certain discomfort...maybe even a little bit of nausea." [48]

Sensations and emotions experienced in IVR

- "With my ears listening and my eyes watching, I forget about the unpleasant things in my heart." [16]
- "It's amazing to look at the birds...Oooh, now I'm getting dizzy [from looking over the edge]...It feels like I'm really about to go downhill!" [9]

Embodied experiences in IVR

- "I mean you could do [any movement] with your fingers and it didn't show up [on your avatar]." [14]
- "...to get any real benefit out of [social VR], you'd have to believe that [the avatar represented] that person. They would have to show some sort of emotion...there wasn't the interaction." [14]
- "*While VR is often described as an individual experience, our results suggest that VR can act as a powerful tool to provoke social interaction and thus counteract the high levels of social isolation*..." [15]

Textbox 4. Illustrative quotes for the descriptive theme of perceptions of immersive virtual reality (IVR) and its subthemes.

Preconceptions of IVR

- "I really didn't think it would be anything that I would enjoy, and I certainly didn't think it was something I could use, however I was intrigued to find out about virtual reality was like." [45]

Perceptions of IVR during and after use

- "This technology is very good, I think it encourages more...it is a thing with a good look, I would give 10 for the glasses, I found it very good, great!" [48]
- "This is what I've been wanting all along." [9]
- "What I did here for me today was new. I never did it." [48]
- "I liked the glasses better because it is different, right?" [48]

Descriptive Themes

Practical Aspects of IVR Use

This theme was discussed in 13/13 of the studies and illustrates older adults' experiences interacting with IVR hardware and software as well as the challenges that arise when facilitating IVR interactions for them.

Interacting With IVR Hardware and Software

Participants in 11/13 of the studies reported issues with the HMD, including that it was too heavy [9,44,45,48,50]; caused general discomfort [9,15,16,44,50]; caused disorientation and imbalance [44,46]; and caused feelings of being trapped, confined [45], afraid, or anxious [16,45]. Difficulties with the HMD being too small to wear with glasses were also described [14,44,46,48,50,51]. Although a range of issues were raised regarding the HMD, 3/13 of the studies reported that the HMD was generally tolerated by participants [9,14,15].

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Issues with the handheld controllers were reported in 5/13 of the studies and included poor ergonomics of the controllers [15,45] and the awkward feeling and positioning [15,45] and smoothness of the buttons [45]. The number of buttons also caused problems, with participants forgetting the function of each of them over time [45]. Issues with handheld controllers were not described in all studies, and some studies reported that participants could use the handheld controllers confidently [15,44] and enjoyed the added control that the handheld controllers gave them in the virtual environment [44]. Of note, the number of buttons that participants had to use was not reported in the extracted data, making it difficult to compare across studies.

Perceptions of the audiovisual quality of IVR hardware varied across studies [14,16,45,48-52]. A total of 5/13 of the studies reported some form of audiovisual issue [14,45,49-51], with feedback that the volume was not at the right level or was not clear enough [45,49-51] or that sound coming from the physical environment could negatively affect the IVR experience [45]. Older adults believed that the resolution of the display must be of high enough quality to ensure a positive experience [50,51]. A study raised the issue that only the participant could be sure if the lenses were fitted correctly, with the researcher never being certain whether the image they were viewing was unclear or just not fitted correctly on the participant's head [14].

In total, 6/13 of the studies reported feedback from participants on how the body tracking in IVR influenced their experience [14,15,44,48,50,51]. Issues included feelings of nausea and dizziness [48] and the virtual handheld controllers disappearing from the screen in the virtual environment [44]. Ensuring that the geopositional tracking does not negatively affect the participant was also discussed, with some participants feeling that the origin of the sound was confusing and that moving content made it more difficult to hear audio while also increasing feelings of nausea [14,51].

A total of 11/13 of the studies described feedback on the content presented, specifically the various objects and scenes inside the virtual environment and participants' experiences navigating them [9,14-16,44,46-48,50-52]. Participants preferred still content to moving content [44,51] and preferred content that was familiar [52], in particular, content similar to past experiences in real life [44]. An important suggestion made was customizing the moving content experienced in the virtual environment to offset the effects of motion sickness [51]. Participants showed a strong preference for tailoring the content to their own interests [15,16,47]. They enjoyed the adaptive nature of the content [15], suggesting also that there could be more "diversity" in the content displayed in IVR, although it was not specified what exactly this content could be [52]. There were only a few negative comments about the content, with some content causing nausea or being too intrusive or incompatible with preferences [16,50,51].

In 4/13 of the studies that described participants' experiences navigating the virtual environments, participants had little issue in doing so [44,48,50,52]. Participants found it easier to interact with the virtual environment after a few practice attempts [52] and also once the equipment was fitted correctly as this enabled them to focus on using the handheld controllers [50]. Participants were also able to interact with the virtual objects such as other virtual avatars [48,50], with a participant explaining that a virtual avatar was inviting her to dance with them [48].

Risks and Requirements of IVR Use

With regard to health and safety [9,14-16,44-46], it was clear that older adults found it dangerous to use an HMD on their own as they were unaware of their physical surroundings when wearing it [9,46] and would like to have someone present to reassure them that they were safe [46]. Self-awareness of HMDs that were tethered to a computer also caused concerns as participants were worried that they would damage the cable or be electrocuted if they stood on it [45]. Weak vision, high blood pressure, and motion sickness brought about feelings of dizziness and discomfort for some [16], whereas others felt unsteady when using the equipment [44]. However, in another study, participants reported not feeling any dizziness or nausea during their IVR experience [14].

Specific risks for wheelchair users described in 1/13 of the studies included overreaching for an object in the virtual environment and falling from their chair, injuring their arms when interacting with the virtual environment because of high armrests, and releasing the brakes of the wheelchair to allow for more movement causing simulator sickness [15]. The authors recommended ensuring that the chair or wheelchair was positioned correctly so that participants could reach virtual objects without having to overreach and risk falling [15]. Despite these issues, other studies found that participants reported having a positive experience with IVR from a sitting position [44,50].

The physical capabilities of the participants and how that influenced their experience with IVR were also reported [9,15,16,44,47,48,50,51]. Having impaired hearing or vision hindered the participants' experience with IVR [16,50,51]. A lack of mobility also prevented some participants from making the most of the full 360° experience [9,47,48,50], where some found it difficult to turn themselves to see other features in the environment [50]. This also highlighted that the experiences need to be tailored to the participants' own capabilities so that they can experience the virtual environment to its full potential [47,48], particularly when people have varying levels of capabilities regarding their use of IVR equipment [15]. In one case, being able to visit places where they could not physically go themselves brought about a heightened sense of immobility [16]. However, in contrast, participants also reported that IVR could give back agency lost through aging because of physical and mental decline [14,15,50], affording them the opportunity to explore places and take part in activities that, if they were to do in reality, might raise concerns about safety among their family members and other key stakeholders [16].

The need for assistance when using IVR was also apparent [44,46,50]. Participants were concerned that they would not remember how to use the technology at a later stage [50]. The authors voiced some concern that participants would need assistance in setting up the equipment at this later stage [50]. Where reported, participants with greater previous digital technology experience needed less support using the equipment

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than those with less experience [44]. However, even participants with less experience found the technology easy to use once it was explained to them [46].

Experiencing Unique Features of IVR

This descriptive theme consists of 3 subthemes exploring participants' experience of presence and immersion, the emotions experienced in IVR, and their experience of embodiment.

Presence and Immersion

A total of 10/13 of the studies reported participants' experiences and perceptions of presence and immersion in IVR [9,14-16,46,48-52]. Participants reported that the feeling of presence made the experience feel more real [15] and allowed them to engage with objects in the virtual environment as if they were really present [9]. Participants from 3/13 of the studies explicitly reported enjoying the experience of presence [9,16,48]. By contrast, a number of participants in 1/13 of the studies had some feelings of anxiety and nervousness because of the experience of presence in the immersive environment, although no specific reason for these feelings was given [16].

A total of 1/13 of the studies reported that the more participants were immersed in the virtual environment, the more it enhanced their experience [48]. Greater immersion provided a heightened travel experience when exploring places around the world [15,16], enabled participants to escape from their own reality [50], and simulated past experiences in a realistic way [49]. Some participants were not convinced by the immersive nature of the technology and felt that they were "passive observers" as they did not feel as if they were in the place they were supposed to be [50]. Participants needed to be able to interact with the content in the virtual environment to make the experience realistic and believable [14], and more familiar virtual environments and situations made the experience more real [48]. Many participants reported really enjoying the immersive nature of IVR [9,14,16,48,52], with only one participant reporting negative sensations because of the immersive experience [48]. This participant also reported enjoying their experience with IVR, suggesting that the positive effects of the experience offset the negative sensations felt.

Emotions Experienced in IVR

Emotions experienced by participants were referred to in all studies (13/13) [9,14-16,44-52] and appeared to be a central part of the IVR experience.

Participants from 8/13 of the studies reported experiencing some form of positive emotion because of their interactions with IVR [9,15,16,44,45,48,49,51]. Some made explicit reference to the fact that it was the immersive experience that incited these positive emotions [9,16,48]. General reports of positive emotional experiences with IVR included it having the "wow" factor [45], having fun interacting with virtual avatars in the virtual environment [15], and always laughing when experiencing the virtual content [51].

Excitement was also common [9,16,45,48,50,51]. In most cases, this excitement referred to a heightened sense of emotion toward the virtual content [9]. In one case, the excitement came to a point where a participant became too giddy and needed to sit down and rest for a period [45].

Negative emotions were also experienced by participants, such as feelings of intrusiveness as the virtual experience felt like an intrusion of their personal space and boundaries [50] and feelings of stress and frustration caused by disassociation with the virtual environment and distrust of the electrical equipment [45]. Regarding this final point, a term was created to describe this combination of experiences, referred to by the authors as "3D fears" [45].

Embodied Experiences in IVR

Embodied experiences in IVR were discussed in 4/13 of the studies [14,15,44,49]. Embodiment refers "...to the process of replacing a person's body by a virtual one" [5]. These embodied experiences relate specifically to how participants interacted with their avatar (the body replacing their own body in IVR) and other participants' avatars in a virtual environment as well as how being embodied in an avatar in a virtual environment made them feel.

Where given the opportunity, participants enjoyed creating their own avatars and embodying them in IVR [14]. However, for this experience to be enjoyed, a number of key issues must be addressed. Glitches in body tracking led to concerns over the negative stereotypes associated with aging. A participant felt as if he had developed Parkinson disease when his virtual hands began to shake involuntarily [14]. The authors concluded that their findings illustrated how tracking errors can negatively affect participants' experiences with IVR when they are trying to express social meaning through nonverbal cues. A critical point closely related to this was that tracking errors also led to participants feeling as if they did not have control over their avatars and, by extension, their own bodies, making them "...particularly sensitive to social stereotypes that render the ageing body as being an object of disgust that makes them 'liable to sanctions, both physical and symbolic'" [14]. Finally, participants thought that the avatars were not realistic enough to facilitate a meaningful social interaction [14].

The power of embodiment and its implications for socialization were also linked to alleviating social isolation [14,15]. However, the authors 1/13 of the studies highlighted that, although embodiment in a virtual environment for one individual may alleviate social isolation and loneliness, it may also emphasize the limitations that another individual might have if they are not capable of exploring the scenes presented in the virtual environment in reality [44].

Perceptions of IVR

This descriptive theme explores older adults' perceptions of IVR, with the first subtheme outlining perceptions before use and the second outlining perceptions during and after use.

Preconceptions of IVR

Most of the preconceptions reported were negative [15,44,45], with a general sense that IVR was a "frivolous undertaking" with little benefit to older adults and better suited to younger generations [45]. Some participants worried that they would forget how to use the handheld controllers [15], whereas others

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were concerned about whether their glasses could be worn with the equipment and, if so, whether the HMD would damage the lenses of their glasses [44]. In contrast, participants from 1/13 of the studies hoped that IVR would "broaden their horizon" [47].

Perceptions of IVR During and After Use

This subtheme reports specifically on participants' overall perceptions of the technology rather than on any specific feature [9,14-16,44-46,48-52].

Feedback provided by participants during and after use was mostly positive [9,14,16,46,48,49,51]. Authors from 1/13 of the studies reported that participants were excited and curious about IVR and were keen to learn about its potential benefits [14]. A participant from another study went as far as to say that it was a technology that had been missing from their life [9].

Novelty experienced in IVR was identified as a distinct pattern in the data [16,48,50,52], usually referring to the unique features IVR has that other technologies do not, such as the ability to completely immerse a participant in a virtual environment [16]. In general, although not explicitly stated in some cases, this novelty referred to positive experiences that participants had with IVR [48].

A number of negative responses to IVR were also reported [16,45,50]. Some participants preferred technologies that did not require an HMD [50]. Others said that they already had enough devices in their lives and did not need another one [50]. The authors of 1/13 of the studies reported that participants found IVR too overwhelming [45], which was supported by additional feedback suggesting that IVR was not suitable for older adults [16].

Analytical Themes

A total of 3 analytical themes were developed based on the descriptive themes to go beyond what was reported in the original studies to generate new meaning and tell a story about older adults' experiences and perceptions of IVR.

Tolerating the Bad to Experience the Good

A focus of the descriptive themes related to older adults' interactions with IVR as well as how these experiences were facilitated (practical aspects of IVR use [9,14-16,44-52]). These accounts included a range of issues that arose while interacting with both the hardware and software as well as positive and negative accounts of the IVR experience (experiencing unique features of IVR [9,14-16,44-52]). On the one hand, many of the negative accounts could be perceived as disincentives for future IVR use that offer little redeeming features for older adults to revisit. However, when considering many of the participants' experiences as a whole, it was clear that a few changes to facilitate their experience with this technology could greatly enhance their interactions with it. For instance, although some issues relating to comfort and usability were raised, a keyword used in 1/13 of the studies to describe how these issues were experienced was "tolerable" [14]. Many participants across these studies were willing to tolerate some of the discomforts that accompany existing IVR technologies to experience features such as immersive networking with other older adults [15]. A striking pattern in the data was the fact that, despite the numerous issues raised by participants, the novel experiences that IVR afforded them in many cases outweighed the nuisances caused by the equipment.

Buying Into IVR: Don't Judge a Book by Its Cover

There was a temporal pattern identified in the data that consisted of older adults' perceptions of IVR across stages of IVR use (perceptions of IVR [9,14-16,44-52]). It began with older adults' perceptions of IVR before use, followed by their perceptions during and immediately after use. This pattern illustrates the importance of users' preconceptions of a given technology and how they can differ from their actual experience with it. The participants' perceptions after use provided greater insight into what older adults like and dislike about IVR and how the experience can be improved before future use.

It was clear that participants generally had low expectations for their experience with IVR, with concerns that they would not be able to use it or that it would simply be a pointless endeavor as they believed that they would have no use for it in their everyday lives [45]. However, once participants had experienced IVR, there was a notable change in their views toward it. Many participants were excited about the opportunities IVR offered them in their lives, enjoying the various novel features such as the 360° view and networked activities [15,16]. This change in impression voiced by many of the participants suggests that there is a discrepancy between how IVR is perceived before and after use, with a generally negative impression of the technology before use changing to a generally positive impression after use.

"It Proves to Me I Can Do It"

This analytical theme conveys the added agency that IVR afforded older adults in several studies. It draws on the wide range of activities that IVR offered to older adults and how these activities appeared to increase agency in this cohort, which was apparent across almost all the descriptive themes (practical aspects of IVR use [9,14-16,44-52] and experiencing unique features of IVR [9,14-16,44-52]). It illustrates an important point about the need to give back agency lost by older adults with growing frailty and immobility as well as the transition from independent to assisted living: "It proves to me I can do it [participate in an IVR activity], it's been a long while since I did anything like that" [46]. The activities that older adults in these studies experienced and shared their views on highlight that IVR provides a platform for older adults to access certain activities and environments more easily than in the real world because of limitations caused by aging, as well as providing activities that they are able to follow and take part in as they are tailored to their needs. It was clear that this freedom to take part in these sought-after experiences in IVR on their own terms was an important feature of IVR for many participants. As such, IVR is conveyed as a pathway to this increased agency in this cohort.

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Discussion

Principal Findings

This review synthesized 13 qualitative studies exploring older adults' experiences and perceptions of IVR. The thematic synthesis explored older adults' experiences interacting with IVR and what challenges arise when facilitating their use of IVR; the unique features of IVR that older adults experienced, such as presence, immersion, and embodiment; and older adults' overall preconceptions of IVR and perceptions of IVR during and after use. The confidence that could be attributed to each finding, assessed using the GRADE-CERQual approach, ranged from high to moderate, with most findings given a moderate rating.

This review did not intend to be exhaustive in its interpretation of all these topics, nor did it intend to offer an exhaustive list of design considerations for future IVR use in this population. It aimed to tell a story about the key findings of this synthesis that other researchers can draw on when designing IVR experiences for older adults. It aimed to go beyond the practical design considerations already offered in papers such as that by Abeele et al [55] to provide a more empathetic interpretation of the experiences older adults have had with IVR to date. By *empathetic*, we refer to the researcher or technology designer putting themselves in the shoes of the end user—in this case, older adults—when exploring these individuals' experiences and perceptions of a technology [56]. This approach responds to the WHO's call for more age-friendly practice [1,10], which endeavors to build infrastructures that older adults can avail of that will enhance their quality of life.

In the Context of Other Research

Conflicting participant experiences were present across the synthesis. These conflicts included differences in older adults' experiences of dizziness and nausea [14,44], wearing the HMD [9,14,15,44,46,48,50,51], and sitting while using IVR [15,44,50]. These conflicts highlight that there is a need for such features to be adaptive to older adults' experiences with IVR. This suggests that an assessment of their capabilities could be completed before they use the equipment to tailor the IVR experience to participants' physical and mental capabilities [47,48]. A key element of this finding is the importance of tailoring the experience to older adults' needs and preferences. Previous research has generated a list of key design features that can be used to help solve issues identified through older adults' experiences reported in this review [55].

A striking finding from this synthesis was the level of agency that the IVR equipment afforded older adults while in virtual reality. It was clear that older adults experienced greater levels of agency during their IVR experience, in some cases enabling greater levels of agency than they had in the real world [14,15,44,50]. Parallels between this finding and previous research exploring the applications and implications of IVR can be made, with equipment such as handheld controllers affording participants features such as illusionary agency over the avatar they embody in the virtual environment [5]. This illusory agency affords participants enough autonomy to take part in experiences that may not be available to them in their own reality. Older adults can also be negatively affected by the added agency they experience in IVR, where it may sometimes only emphasize their own limitations in reality [44]. A balance must be struck between what is perceived as a freeing and beneficial activity by older adults through using IVR and what can be perceived as a reminder of their own age-related limitations.

Another salient finding of the synthesis was the change in participants' generally negative perceptions of IVR before use to generally positive perceptions after use. This is in line with existing research suggesting that the process of accepting a technology resembles a life cycle, with preconceptions of a technology being an essential part of this life cycle as they play a role in whether the participant will eventually adopt the technology [18].

There were clear signs that participants were generally happy to tolerate certain nuisances inherent to some of the existing IVR technology features to experience what they considered to be meaningful activities [15]. Social connection in IVR was one of these sought-after activities for many participants because of the added opportunity it gave them to meet others outside their sometimes restrictive environment [14,15]. These novel interactions experienced by participants incited a newfound sense of excitement, in many cases leading to more motivation to take part in activities in IVR. However, current research supports the need for improvement in existing IVR features to facilitate more meaningful IVR activities such as social interaction [7]. Evidence suggests that older adults appreciate certain features that IVR offers them, such as added anonymity, which encourages introverted participants in particular to share more in IVR social circles [7]. However, IVR is still considered too complicated for older adults to engage with as a means of taking part in these social networking experiences when compared with face-to-face communication as well as other computer-mediated technologies such as FaceTime or Skype [7].

A key finding of this review is the success some researchers had in identifying and offering solutions to some of the nuisances reported by participants through the methodologies they used to explore this topic [7,14,15], such as participatory action research. This approach, along with other co-design approaches such as Patient and Public Involvement [57], can help improve the usability and accessibility of IVR technologies for older adults as the technology continues to rapidly evolve over time. Co-design approaches enable researchers to iterate on versions of IVR hardware and software more rapidly without the need to repeatedly collect and analyze data, which is essential given the rapid turnover of new IVR technologies in today's market [3].

Implications and Recommendations

In line with the primary review question—"what are older adults' experiences and perceptions of IVR?"—this synthesis offers an insight into the experiences older adults have had with IVR and their perceptions of these experiences. The approach to implementing and exploring IVR needs to be taken with care and empathy for the individual [56] as our results demonstrated variation in experiences and perceptions of interacting with IVR. It is hoped that this empathetic perspective offers

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researchers in this field more direction when considering how to first approach introducing IVR to older adults and later ensuring that their IVR experiences are facilitated in a way that makes it more meaningful for them. This empathetic approach to design is in line with the age-friendly practice of the WHO [1,10], where infrastructures that are put in place to maintain and enhance older adults' quality of life are designed to specifically support older adults' needs and preferences.

With regard to the secondary review question "what are the barriers and facilitators to older adults' use of immersive virtual reality?" the descriptive themes illustrated the barriers older adults face when using IVR, including challenges regarding health and safety when using IVR, wheelchair and stationary use during IVR activities, physical capabilities when using IVR, and the assistance needed to interact with IVR. As there was little reporting on the facilitators of IVR use in the extracted data, future research needs to focus on exploring solutions that can help older adults and other key stakeholders overcome the barriers outlined in the synthesis. With regard to the secondary review question "do older adults find IVR acceptable?" participants' perceptions indicated that, once they tried IVR, they generally enjoyed the experience despite some of the shortcomings of the technology. Exploring further why exactly participants find IVR acceptable is important in future research as it is now considered a key determinant of whether a technology will be adopted in the future [18].

As outlined in the Introduction section, older adults require greater assistance as they age to continue leading a fulfilling and independent life [10]. The descriptive and analytical themes highlighted that IVR can provide a platform for older adults to access activities and environments more easily than in the real world because of limitations caused by aging, as well as providing activities that they are able to follow and take part in as they are tailored to their needs. Moreover, it was clear that older adults enjoyed and ascribed meaning to their IVR experiences, with reports that, in some cases, the activities in IVR were more appealing than those offered to them in their real environment [15]. Such outlets increased people's desire to return and try these experiences again as they afforded older adults more opportunities to take part in activities that they were able to engage in and enjoy.

On the basis of the review and synthesis of findings, there are a number of recommendations for future research conducted in this area. First, it is essential that researchers provide a comprehensive report on the nature of participants' interactions with IVR. There were several cases where it was challenging to compare features across studies as there was not enough detail given on the features that participants interacted with. For example, participants across a number of studies found the handheld controllers difficult to operate, but it was not specified how many buttons participants were using, which is a key consideration when assessing what level of complexity is within certain participants' capabilities. In line with the outcomes of GRADE-CERQual, authors also need to explore further their relationship with the research participants. Reflexive practice of this nature offers both the authors and readers a greater understanding of the context within which the study was designed and the perspectives of the authors that could potentially influence future interpretations of the findings [43]. The GRADE-CERQual approach also highlighted the lack of clarity regarding ethical considerations taken in several studies. It is essential that researchers report explicitly on these considerations, especially when working with vulnerable cohorts.

Strengths and Limitations

The review protocol was published [22], registered on PROSPERO, and preregistered on the Open Science Framework, where an open-source repository of all the review materials has been stored and updated (Multimedia Appendix 1). The ENTREQ guidelines were followed when writing the report [23]. The review team had a wide range of expertise, ensuring that the interpretations made in the synthesis were accessible across multiple relevant disciplines. Thematic synthesis was an appropriate method for data synthesis as it allowed the reviewers to stay close to the results of the primary studies, which facilitated "...the explicit production of new concepts and hypotheses" [38]. The search strategy was broad. In total, 2 reviewers screened the studies to reduce bias. This review provides a new perspective on how older adults' experiences and perceptions of IVR can be interpreted, taking a more empathic and experiential approach to data synthesis rather than focusing on irreducible, quantifiable design considerations.

The exclusion of non-English studies is a potential source of bias. However, because of the lack of available resources, no translator could be used for the non-English studies identified. Gray literature was also not searched, which limited the included studies to published works. The reasoning for excluding gray literature was because a scoping review of the gray literature before conducting the systematic review search indicated that there was limited qualitative data available that were not published in academic journals.

Conclusions

This review offers an insight into the experiences older adults have had with IVR to date. With a few improvements to existing IVR hardware and software, focusing also on how it is first presented to older adults, IVR may arise as a new outlet through which older adults living both independently and in residential aged-care facility could take part in a range of meaningful activities that are tailored to their needs and preferences.

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Conflicts of Interest

None declared.

Multimedia Appendix 1
Embase search strategy and osf link.
[DOCX File , 21 KB - games_v10i4e35802_app1.docx]

Multimedia Appendix 2
Data extraction protocol.
[DOCX File , 15 KB - games_v10i4e35802_app2.docx]

Multimedia Appendix 3
Reflexive thematic analysis mapped onto thematic synthesis.
[DOCX File , 15 KB - games_v10i4e35802_app3.docx]

Multimedia Appendix 4
Virtual reality applications.
[DOCX File , 19 KB - games_v10i4e35802_app4.docx]

Multimedia Appendix 5
Immersive virtual reality activities.
[DOCX File , 18 KB - games_v10i4e35802_app5.docx]

Multimedia Appendix 6
Quality appraisal summary.
[DOCX File , 15 KB - games_v10i4e35802_app6.docx]

Multimedia Appendix 7
Grade-cerqual summary.
[DOCX File , 20 KB - games_v10i4e35802_app7.docx]

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Abbreviations

ENTREQ: Enhancing Transparency in Reporting the Synthesis of Qualitative Research
GRADE-CERQual: Grading of Recommendations Assessment, Development, and Evaluation-Confidence in the Evidence from Reviews of Qualitative Research
HMD: head-mounted display
IVR: immersive virtual reality
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
WHO: World Health Organization

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Original Paper

Development of a Novel Home-Based Exergame With On-Body Feedback: Usability Study

Alexandra Schättin[1*], PhD; Jordan Pickles[2*], MPhil; David Flagmeier[3], BA; Benjamin Schärer[2], MSc; Yanick Riederer[1], MSc; Stephan Niedecken[1], Dipl; Stefan Villiger[3], BSc; Roman Jurt[3], BA; Nicole Kind[3], Dipl; Sam N Scott[2,4*], PhD; Christoph Stettler[2*], MD; Anna Lisa Martin-Niedecken[1,3*], PhD

[1]Sphery Ltd, Zurich, Switzerland

[2]Department of Diabetes, Endocrinology, Nutritional Medicine and Metabolism, Bern University Hospital, University of Bern, Bern, Switzerland

[3]Department of Design, Institute of Design Research, Zurich University of the Arts, Zurich, Switzerland

[4]Team Novo Nordisk Professional Cycling Team, Atlanta, GA, United States

[*]these authors contributed equally

Corresponding Author:
Anna Lisa Martin-Niedecken, PhD
Department of Design
Institute of Design Research
Zurich University of the Arts
Pfingstweidstrasse 96
Zurich, 8031
Switzerland
Phone: 41 79 775 06 73
Email: anna.martin@zhdk.ch

Abstract

Background: With more than 1.4 billion adults worldwide classified as physically inactive, physical inactivity is a public health crisis leading to an increased risk of cardiometabolic diseases. Motivating and engaging training strategies are needed to tackle this public health crisis. Studies have shown that exergames, games controlled by active body movements, are potentially usable, attractive, and effective tools for home-based training. The ExerCube (by Sphery Ltd) has been developed as a physically immersive and adaptive functional fitness game. The development of a home-based version of the ExerCube could increase accessibility, reduce barriers to exercise, and provide an attractive solution to improve physical and cognitive health.

Objective: The aim was threefold: (1) to develop a usable home-based exergame system, (2) to evaluate the usability and training experience of the home-based exergame and its early-stage on-body feedback system, and (3) to identify avenues for further user-centered design iterations of the system.

Methods: A total of 15 healthy participants (mean age 25, SD 3 years) completed 2 laboratory visits consisting of four 5-minute exergame sessions. In each session, the on-body feedback system provided a different feedback modality (auditory, haptic, and visual feedback) to the participant. Following the second visit, participants completed a range of assessments, including the System Usability Scale (SUS), the Physical Activity Enjoyment Scale (PACES), the Flow Short Scale (FSS), the Immersive Experience Questionnaire (IEQ), and a rating of perceived exertions (RPEs) both physically and cognitively. Participants answered questions regarding the on-body feedback system and completed a semistructured interview.

Results: Usability was rated as acceptable, with a SUS score of 70.5 (SD 12). The questionnaires revealed medium-to-high values for the training experience (FSS: 5.3, SD 1; PACES: 5.3, SD 1.1; IEQ: 4.7, SD 0.9. Physical (mean 4.8, SD 1.6) and cognitive (mean 3.9, SD 1.4) RPEs were moderate. Interviews about the on-body feedback system revealed that the majority of participants liked the haptic feedback and the combination of haptic and auditory feedback the best. Participants enjoyed the distinct perceptibility, processing, and integration of the exergame and its supportive and motivating effect. The visual feedback was perceived less positively by participants but was still classified as “potentially” helpful. The auditory feedback was rated well but highlighted an area for further improvement. Participants enjoyed the training experience and described it as motivating, interactive, immersive, something new, interesting, self-explanatory, as well as physically and cognitively challenging. Moreover, 67% (n=10) of the participants could imagine exercising at home and continuing to play the exergame in the future.

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Conclusions: The home-based exergame and its early-stage on-body feedback system were rated as usable and an enjoyable training experience by a young healthy population. Promising avenues emerged for future design iterations.

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KEYWORDS

exergame; iterative design; home-based exergame; on-body feedback; usability; training experience; gameplay experience; home-based exercise; serious games; physical activity

Introduction

Physical inactivity, defined as levels of physical activity lower than those generally recommended for optimal health as well as disease and premature death prevention [1], is a public health challenge [2], with more than 1.4 billion (~1 in 4) adults worldwide classified as physically inactive [3]. A number of common barriers to exercise, including a perceived lack of time, lack of motivation, financial restrictions, limited access to facilities, and appropriate equipment, as well as environmental factors such as bad weather, have been linked to low physical activity levels [4,5]. Home-based exercise has the potential to overcome some of these barriers to exercise, as it alleviates the need for travel and, if done indoors, overcomes the barrier of bad weather. The COVID-19 pandemic has accelerated this trend, with many people exercising at home due to the closure of sports facilities [6].

To date, many home-based exercise studies have focused on simple body weight exercises, resistance banded training, and traditional training methods (ie, walking and jogging) [7-12]. While these approaches are generally effective at improving markers of health, they may be hampered in their effectiveness due to motivational issues interfering with regular exercise. New, engaging, and effective strategies may help to overcome such common exercise barriers. Furthermore, these strategies have the potential to increase the physical activity level to the World Health Organization recommendation of at least 150-300 minutes of moderate intensity or 75-150 minutes of vigorous intensity physical activity per week, or an equivalent combination [13], in an increasingly inactive population.

Exercise games (exergames) concurrently combine physical and cognitive training through an integration of physical exercises within video games [14]. Exergames have been shown to improve both cognitive and physical health [15-19] while providing a more attractive exercise setting compared to traditional gym-based exercises [17,18,20,21]. Regarding the integration and use of exergames at home, the literature shows that exergaming in a home-based setting elicits high training adherence and compliance [22-24]. Furthermore, studies showed acceptable to high rates for feasibility and usability in terms of home-based exergames in children and older adults [22,25]. Moreover, results demonstrated favorable emotional experiences as well as positive responses regarding motivational aspects [22,23]. Regular exergame system updates, including further attractive games, could help to keep the experience and motivation at a high level [25]. In addition, exergaming was proposed to be an effective training approach to maintain physical activity at home during the COVID-19 pandemic [26]. Nevertheless, literature points out the importance of flawless technical functionality [22], as error-prone systems can exceed external support and lower training motivation [25]. Moreover, social and clinical guidance may remain necessary for sustained exergame engagement at home in certain settings [27]. Overall, exergaming has the potential for an attractive and effective home-based training strategy.

The ExerCube (Sphery Ltd), a physically immersive mixed-reality functional fitness game [21,28], has been found to provide an equally enjoyable and motivational experience when compared to traditional training methods [21,29]. Within the ExerCube, players are surrounded by 3 walls, which serve as projection screens and a haptic interface for energetic bodily interactions. A customized motion tracking system follows players' movements. The ExerCube incorporates technology that adapts the game in real time to the individualized requirements through changes in training intensity and in-game difficulty based on continuous heart rate (HR) tracking and the user's in-game performance [29,30]. The potential for the ExerCube as a feasible and effective exergame has been corroborated before [21,29,30]. However, the stationary version was originally designed for use within a gym-based environment and not for use in home-based environments.

To make the ExerCube available to a broader population, thereby reducing major exercise barriers, the development of a home-based version of the ExerCube would be advantageous. Therefore, the aim of this study was threefold: first, to develop a usable home-based exergame system by translating the spatial guidance and the motivating haptic feedback of the stationary version of the ExerCube into an exergame setting for home use; second, to evaluate the usability and training experience of the home-based exergame and its early-stage on-body feedback system; and third, to identify avenues for further user-centered design iterations of the system.

Methods

Design Process of the On-Body Feedback System

In an iterative, user-centered design process, an immersive on-body feedback system was developed to preserve the benefits of the physically immersive setup of the ExerCube (Figure 1A) for use in the home (Figure 1B). The first phase of the design process was to analyze the existing stationary exergame system and determine its technical opportunities, focusing on the attributes allowing for an immersive training experience. The most important finding was that the haptic and spatial experience provided by the 3 walls in the ExerCube had to be translated into an on-body feedback system. The focus was on using existing hardware as well as the player's body to implement an additional feedback system.

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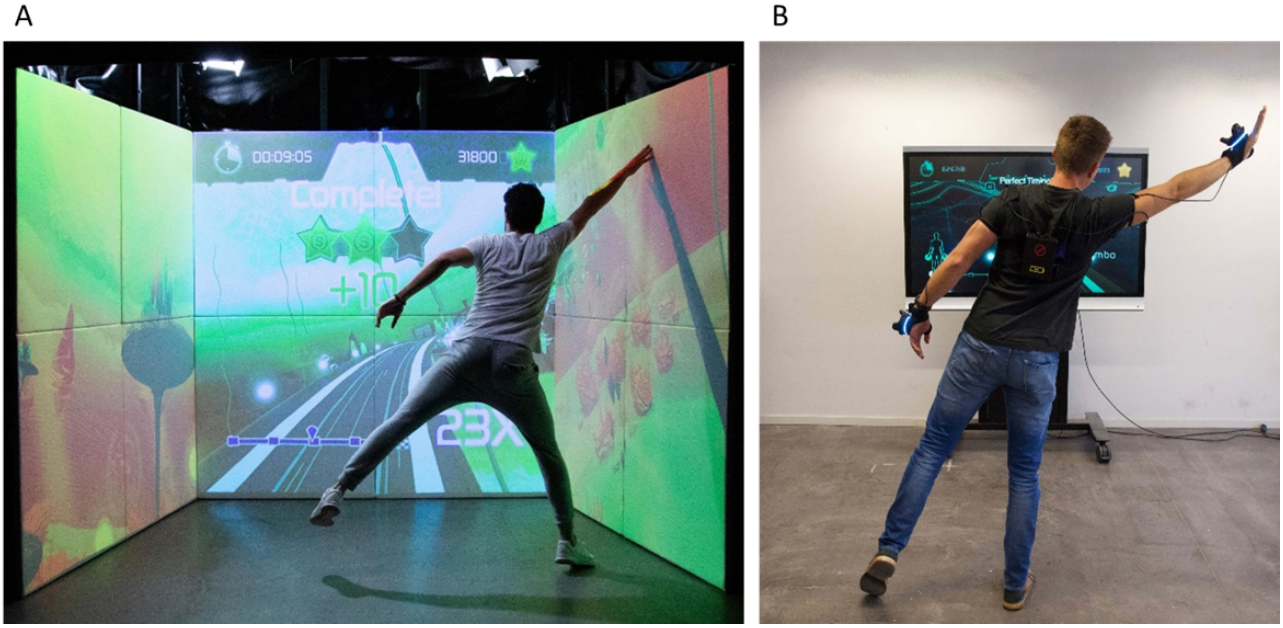
Figure 1. Comparison of the original full-size ExerCube and the first iteration of the home-based version. (A) The original ExerCube setting with the 3 walls. (B) The home-based exergame and its early-stage on-body feedback system (gloves). Note that in both versions, the user has sensors on the wrists and ankles so that movements are followed by the HTC Vive trackers. In the home-based version, feedback is provided either through auditory, haptic, or visual stimuli or through a combination of these modalities.



Following a rethinking process, different concepts for the on-body feedback system were elaborated by industrial designers and sports scientists. To ensure that these concepts were user-centered, a focus group session was conducted with 5 young adults who were potential target users of a home-based exergame. The aim of the focus group interview was to explore the target group's previous experiences with exergames; to define needs, preferences, and expectations for an optimal exergame experience; and to provide feedback about the elaborated on-body feedback systems using a semistructured interview guideline. The semistructured interview guideline was developed based on questions about home-based exergaming and especially on extending the gaming experience with an on-body feedback system.

Based on the feedback from the focus group session, the first version of the home-based exergame featured feedback gloves that were developed to provide the spatial perception and motivating haptic feedback needed to interact with the game. Vibration motors were used to resemble the haptic sensation of touching and punching without the need for physical walls. Visual and auditory feedback through light and sound were implemented as additional modes of interaction, exploiting the immersive experience of the game.

Usability Study

Study Design and Procedure

Healthy adults (age ≥18 years) participated in this study. Participants provided informed consent before participating. Participants attended 2 visits at the Inselspital University Hospital, Bern, Switzerland. Visit 1 familiarized the participants with the exergame through an in-game tutorial that provided in-depth instructions on how to complete each physical movement correctly before participants performed the exercise in a short sample of the game. Participants then completed four 5-minute exergame sessions, with each session separated by approximately 2 minutes of recovery time. Each session provided a different feedback modality to the participants (ie, whether they received feedback via auditory, haptic, or visual stimuli; Figure 2). In visit 2, participants completed the same four 5-minute exercise sessions as in visit 1. However, the order in which exercise sessions were completed was random. In both visits, participants were asked questions after completing each individual exergame session to assess their perception of the on-body feedback system. Following completion of all exergame sessions within visit 2, participants were asked to complete a range of questionnaires to assess usability and their exergame training experience. Participants then completed a semistructured interview with a member of the research team to assess their overall exergame experience. All interviews were conducted by author BS to eliminate researcher bias.

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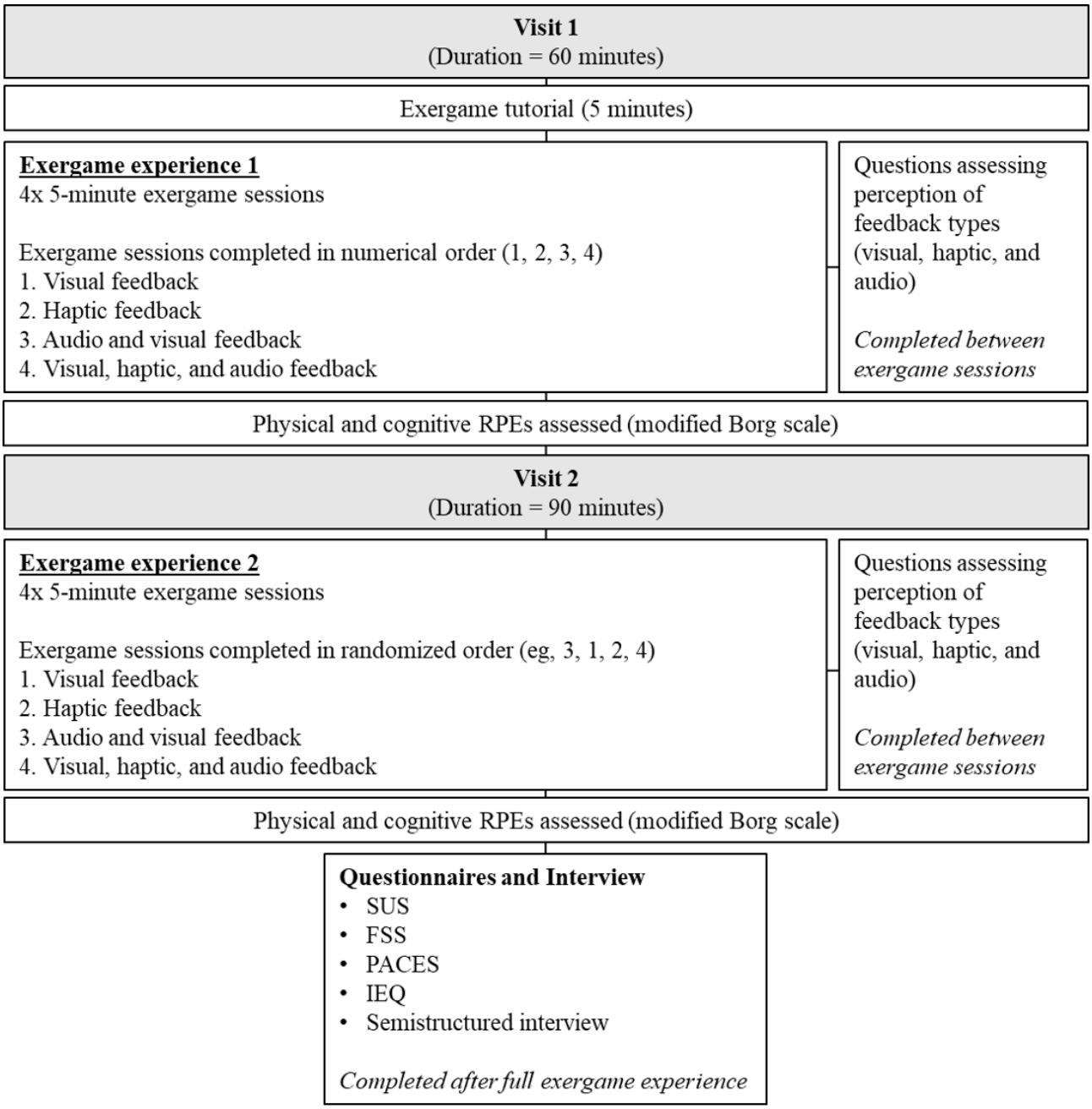
Figure 2. Protocol overview. Visual: light response on the hand sensor for correct movement; haptic: vibration response on the hand for correct movement; auditory: sound response for correct movement. FSS: Flow Short Scale; IEQ: Immersive Experience Questionnaire; PACES: Physical Activity Enjoyment Scale; RPE: rating of perceived exertion; SUS: System Usability Scale.



Ethics Approval

This study was granted an exemption from ethical approval by the Cantonal Ethics Committee, Bern, Switzerland (REQ-2021-00061).

Description of the Home-Based Exergame Set-up

"Sphery Racer" (by Sphery Ltd), a single-player game experience designed for the ExerCube setting, was used as the game environment. The "Sphery Racer" asks players to progress along a fast-paced racetrack via an avatar on a hover board. The customized motion tracking system (HTC Vive trackers) transfers the player's movements (based on a functional workout) onto this avatar and thus onto the virtual racing track. Along the race, players are challenged by obstacles that require whole-body, functional physical exercises (eg, squats, lunges, and burpees) and by an additional cognitive challenge that includes quick information processing by deciding which exercise has to be performed when (ie, reaction time and coordinative challenges). Each correctly performed and timed exercise is rewarded with points. Players can advance through 5 game levels. Each level can be reached by performing a certain number of correctly executed physical exercises in succession (combo). Players are also demoted if they make mistakes. The higher the level, the higher the game speed (ie, the quicker appearance of the physical exercise). The greater the physical and cognitive challenge, the greater the point multiplier. To further ensure an ideal workout experience, the home-based exergame incorporates technology that adapts the game speed to the individualized requirements based on continuous HR

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tracking, aiming to keep the players at 80% of their maximal HR.

The newly developed on-body feedback system was integrated into the gloves of the tracking system to provide spatial guidance and motivating haptic feedback through different on-body feedback modalities. Flashing lights (visual feedback), vibration (haptic feedback), and sound (auditory feedback) appeared (depending on the predefined setting, Figure 2) when participants performed the correct exercise in the correct time window. The device illuminated red (visual feedback) when participants committed an error (wrong exercise or incorrect timing). Furthermore, the color of the lights changed depending on the game level (level 1: very dark cyan; level 2: dark blue; level 3: dark cyan-lime green; level 4: moderate orange; level 5: dark magenta).

Assessments of Usability and Exergame Training Experience

Exergame usability was measured using the System Usability Scale (SUS; α=.91) [31,32], consisting of 10 items rated on a 5-point Likert scale (0: not true; 4: true). The overall usability score was calculated and multiplied by 2.5 to give a score out of 100. A score of at least 70 was set for an "acceptable solution" in this study; between 50 and 70 was "marginally acceptable"; and below 50 was "unacceptable" [32,33]. Participants' exergame training experience was evaluated through the Flow Short Scale (FSS; α=.90) [34]. The FSS consisted of 13 items rated on a 7-point Likert scale (1: not at all; 7: very much) and was measured in 4 dimensions: overall flow, fluency of performance, absorption by activity, and perceived importance. For the dimensions of overall flow, fluency of performance, and absorption by activity, scores closer to 7 signal a positive score. For perceived importance, a score closer to 1 is deemed a positive score. Participants' enjoyment of the exergame training was assessed using the Physical Activity Enjoyment Scale (PACES; α=.96) [35-38], which consists of 18 bipolar statements with 7 points between statements. To assess immersion within the game, participants completed the Immersive Experience Questionnaire (IEQ), which consists of 31 items assessed on a 7-point Likert scale (1=strongly disagree; 7=strongly agree) [39]. The IEQ analysis categorizes the responses into the following subcategories: total immersion, challenge, control, real-world dissociation, emotional involvement, and cognitive involvement [39]. The final single-item measure of immersion was measured on a 10-point scale (1: not at all immersed; 10: very immersed). To assess both physical and cognitively perceived exertion, a modified 10-point Borg scale (1: very, very light; 10: extremely heavy) was used [40]. Finally, a semistructured interview was designed to provide a specific evaluation of usability and training experience. The interview consisted of questions in several categories: overall, game software, game control, at-home use, focus, motivation, training (physical and cognitive), and further thoughts, including wishes and ideas.

Data Analysis

Quantitative data (questionnaires and ratings of perceived exertion scales) were analyzed and reported descriptively. The semistructured interviews were assessed by 3 of the authors (AMN, AS, and YR). The authors followed an iterative thematic coding approach (overall experience, game [software], game control [hardware], at-home use, focus, motivation, training, and further thoughts including wishes and ideas) based on qualitative content analysis [41]. The themes for the coding were based on the categories of the semistructured interview that were determined before the study started. For all interviews, the coders individually transcribed and coded the data according to the categories of the interview guidelines. In iterations, the coders discussed the emerging results until an agreement was reached. Finally, 2 of the authors (AMN and AS) further summarized the results to compile the individual statements into main findings.

Results

Participants

A total of 16 participants (n=9 females, n=7 males; mean age 25, SD 3 years) were recruited for the study. One participant did not complete visit 1 due to a technical issue (a connection issue with the battery source of the on-body feedback system); therefore, 15 participants (n=9 females and n=6 males; mean age 25, SD 3 years) completed both study visits.

Questionnaire Responses

The data from the questionnaires are presented in Table 1.

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Table 1. Quantitative data assessing system usability, flow, enjoyment, immersion, and perceived physical and cognitive exertion (N=15).

Measurement	Mean (SD)	Median (IQR)	Range
System usability			
System Usability Scale	70.5 (12.0)	70.0 (65.0-77.5)	47.5-92.5
Training experience			
Flow Short Scale			
Overall flow	5.3 (1.0)	5.6 (5.0-6.0)	2.8-6.3
Fluency of performance	5.5 (1.1)	5.8 (4.9-6.2)	3.3-6.8
Absorption	5.0 (1.2)	5.3 (4.9-5.6)	1.8-6.5
Perceived importance	2.3 (1.3)	2.0 (1.2-2.7)	1.0-6.0
Physical Activity Enjoyment Scale	5.3 (1.1)	5.6 (5.0-6.0)	2.3-6.5
Immersive Experience Questionnaire			
Total immersion	4.7 (0.9)	5.0 (4.4-5.2)	1.7-5.4
Challenge	4.8 (0.9)	4.8 (4.5-5.4)	2.5-6.0
Control	4.5 (1.2)	4.6 (4.1-5.2)	1.0-5.6
Real world dissociation	4.3 (1.1)	4.3 (4.0-4.9)	1.1-5.4
Emotional involvement	4.0 (1.3)	4.0 (3.8-4.9)	1.0-5.8
Cognitive involvement	5.4 (1.3)	5.7 (5.2-6.1)	1.6-6.7
Immersion reliability check[a]	7.0 (2.0)	8.0 (6.3-8.0)	1.0-9.0
Rating of perceived exertions			
Physical	4.8 (1.6)	5.0 (4.0-6.0)	1.5-7.0
Cognitive	3.9 (1.4)	4.0 (3.0-5.0)	1.0-6.0

[a]n=14. Scores presented as mean values, median values, SDs, IQRs, and the minimum and maximum values for each measurement.

Interview Data: On-Body Feedback System

Questions about the on-body feedback system revealed that during visit 1, participants did not notice the flash and colors in the visual feedback mode. However, the red-colored lights, which appeared when an error occurred, were strongly perceived by the participants. The vibration (haptic feedback), as well as the timing of the introduction of this feedback in the game, were immediately registered by the participants. The vibration was perceived as supportive. If the vibration was perceived as distracting, it was only at the beginning, as participants became familiar with the game. The sound (auditory feedback) was strongly perceived. However, the sound was not perceived as pleasant, and the quality was criticized. Many participants preferred the combination of sound and vibration. Few preferred the version with vibration only.

After visit 2, most of the participants recognized when feedback was added or omitted. Almost half of the participants chose haptic feedback (vibration) alone as their favorite feedback, as it was perceived to be discreet and less distracting. Likewise, almost half of the participants preferred the combination of vibration and sound due to the more pronounced feedback and motivating effect. The changes in colors depending on the level were better classified in the second study visit. The flash was not recognized correctly because it was mostly out of the field of view.

In visits 1 and 2, the colors and the flash were neither rated as supportive nor as a distraction. The vibration was perceived very positively by all participants and was not distracting. The use of the sound feedback was also immediately registered by all participants. However, the sound was perceived as too loud by almost half of the participants. Likewise, the sound was described as rather unsupportive due to its poor quality, delayed sounding, and volume. Many participants were even distracted by the sound during the game for the same reasons.

Regarding the attachment of the on-body feedback system with straps on the wrist, about half of the participants found them not annoying, while the rest found this form of attachment rather less comfortable due to sweat, cables, and a battery backpack during exercises.

Interview Data: Overall Training Usability and Experience

Overall Experience

Overall, participants enjoyed the study as well as the gaming and training experiences. They experienced positive feelings during the training and described it as *something new*, *fun*, *innovative*, *cool*, *interesting*, *motivating*, *immersive*, *entertaining*, *interactive*, *intuitive*, *clear*, *simple*, *effective*, and *challenging*.

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Game Software

Most of the participants liked the game (*design*, *dive into another world*, *forget the training aspect*, *new concept*, and *different movements*). Some participants stated that they would suggest adjustments to certain features of the game (*one-sided movements*, *upper body relatively little involved*, and *repetitive exercises*). Furthermore, the game was comprehensible for the majority of the participants (*the game explained what needs to be done*, *at the second training it was already easier*, and *the tutorial explained the exercises*). Participants mentioned aspects to improve the comprehensibility of the game: *timing of the exercises*, *registration of the executed exercises*, and *explanation of the movement execution*. The video game environment and the narrative framework were positively rated or even not noticed by the participants while performing the exergame. Some participants would like to have more variety through alternative game scenarios (eg, *more realistic game environment*) in the future. Furthermore, all the participants noticed that the game adapted to their individual performance skills (speed of the game).

At-Home Use

Participants could imagine exercising at home with the exergame system (*little time and material*, *lockdown [COVID-19]*, *bad weather*, and *for people who do not want to train exposed*). They would install it in their living room, basement, or office and would want to spend a maximum of 5.7 (SD 3.8) minutes installing the system, suggesting that the game should be quick and easy to set up. For many of the participants, their existing TV at home would be big enough to play the exergame at home. Certain aspects were mentioned as reasons why they would not want to use the system at home: *difficult to set up*, *room size*, and *preference to do sport in nature* (eg, *jogging in the forest*).

Focus

All participants focused on the game during the training (*upcoming exercises*, *exercise execution*, *reaching a high score*, *game stimuli*, and *being absorbed by the gaming environment*) and paid less attention to what was happening around them. Few of them paid attention to their body during the training (*inconsistent registration of the movement and position in the room*). The majority of the participants felt immersed in the gaming environment. Some of them felt the immersion was interrupted due to *inconsistent exercise registration of the exercises* or *a delay in the game*. A few participants felt dissatisfied with the current setup and would prefer virtual reality (VR) glasses. Most of the participants were distracted (to varying degrees) from the training intensity by the gaming environment.

Motivation

Participants were motivated to move and get better in the game (*flow feeling*, *high score*, *gaming factor*, *correct movement execution*, and *high combo*). Many of the participants stated that they would be more motivated to train with the exergame than visit a gym.

Training

Furthermore, the majority of the participants felt physically and cognitively challenged by the exergame (*upcoming exercises*, *more in the first training session*, and *the faster or more strenuous the game became the more you had to think*) but not to their limits. Participants identified the following aspects as their biggest challenges: *correct exercise execution*, *timing* (*when the game became fast*), *keeping concentration high*, and *switching from one side of the room to the other side*). For some participants, the movements felt natural, and for others, the movements felt partly natural (*jogging in place was weird* and *execution of the lunges*). Participants would train a maximum of 2.5 (SD 1.0) times per week (range 1-4 times per week) for a maximum of 30.0 (SD 11.7) minutes (range 10-60 minutes) with the fitness exergame.

Thoughts Including Wishes and Ideas

Finally, participants would like to continue to play the fitness exergame in the future, and thus they wished for further extension to keep training motivation at a high level over a longer period: a tutorial with a *more detailed description of the exercises*; *smaller, handier, and more reliable* game controller; *options* regarding feedback selection and the video game environment; as well as *more and different movements for the training*.

Discussion

Principal Findings

The aim of this study was threefold: first, to develop a usable home-based exergame system by translating the spatial guidance and the motivating haptic feedback of the stationary version of the ExerCube into an exergame setting for home use; second, to evaluate the usability and training experience of the home-based exergame and its early stage on-body feedback system; third, to identify avenues for further user-centered design iterations of the system. Study results showed that the home-based exergame and its on-body feedback system were usable for a young healthy population. Regarding the on-body feedback system, participants enjoyed the haptic feedback and the combination of haptic and auditory feedback the best due to their supportive and motivating attributes. Furthermore, questionnaires and the semistructured interview indicated that participants enjoyed the motivating, interactive, and immersive gaming and training experience. Moreover, findings for future iterations of the home-based exergame system emerged from this evaluation process.

Usability of the Exergame and its Feedback System

The SUS score of 70.5 (SD 12) is an acceptable score according to Bangor et al [32,33] and meets the “acceptable solution” value (set at least 70) of this study. Next to the SUS, the system’s usability was also reflected in the participants’ interview responses. Participants quickly understood how to control the exergame and rated it as self-explanatory and comprehensive. Furthermore, participants enjoyed the experience with the prototype on-body feedback system and could imagine using this exergame at home. The result of this study is on par with the literature, showing that participants

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found exergames to be an acceptable and usable solution for training in a home setting [22,25]. Thus, the integrated iterative user-centered design process seems to be an essential aspect of designing usable exergames [42,43].

Nevertheless, certain aspects were mentioned in the interview that would further improve the system's usability and, thus, the gaming experience. These suggestions included analogue (eg, floor markings) or digital (eg, in-game visual or auditory signals) reference points to define the training area for the player. In the stationary ExerCube, the player is surrounded by 3 walls defining the training area. The challenge for future development work is to define the training area in a way that maintains the training experience and flow at a high level for the player. A further challenge that is connected to the training area is the timing of the exercises, meaning when the player has to initiate the movement to meet the target and reach the full score. In the ExerCube, the targets are moving from the front wall to the side wall. Thus, the home-based system should have alternative information that supports the player in deciding the timing of the movement. Another challenge that goes along with the space aspect is the training room, as each user has different space conditions at home. Therefore, the home-based system should have a certain degree of flexibility (eg, via calibration) to adjust to different room situations. Furthermore, the exergame should include further information and explanations of the executed movements. This aspect is even more important for home-based exergame training compared to training in a fitness class that is usually supervised by an instructor.

Regarding the on-body feedback device, the system has to be further developed and integrated into the existing devices (eg, tracking system), allowing the exergame to work as one complete system. This step should increase the usability of the system. Moreover, the visual and auditory feedback have to be improved in order to provide an additional supportive system for the above-mentioned challenges of an at-home exergame system. Furthermore, the feedback should be better integrated into the existing exergame scenario, providing the player with an on-body projected gaming experience. Overall, the study showed that the home-based exergame, as well as its early-stage on-body feedback system, is a usable training system for young healthy adults. Promising avenues and challenges were uncovered that have to be faced in future R&D work to further improve the usability and training experience of the home-based exergame.

Game and Training Experience

The interview results showed that the participants enjoyed the study as well as the training experience. The majority of the participants reported that they felt immersed in the gaming environment and were motivated to move and get better at their game performance. Alongside the interview results, the questionnaire data (FSS, PACES, and IEQ) showed medium-to-high scores, indicating that participants were immersed in the gaming environment, enjoyed the training, and experienced flow feelings during the exergame training sessions. Flow and immersion, especially those generated by exergame training approaches, can divert the player's attention away from the physical effort [29,44-46]. In terms of training motivation, this training experience and the shift in focus could be crucial to increasing intrinsic training motivation and, thus, long-term training motivation and adherence in physically inactive people [46,47]. These findings are in line with previous studies showing that home-based exergames can elicit favorable emotional experiences as well as positive responses regarding motivational aspects [22,23].

Moreover, the exergame training approach has to have an individually effective training load to experience flow [48,49] as well as trigger physical and cognitive improvements when performed over a longer time period. The assessed perceived exertion values showed moderate intensities for the physical and cognitive aspects. This is in line with the interview results, which showed that the participants felt physically and cognitively challenged by the exergame. The World Health Organization recommends at least 150-300 minutes per week of moderate intensity physical activity or 75-150 minutes per week of vigorous intensity physical activity, or an equivalent combination [13].

Overall, the results demonstrated that this exergame and its early-stage on-body feedback system have the potential to be an attractive home-based training solution. The newly developed system triggered similar game and training experiences as shown in previous studies using the ExerCube [21,29,30]. Furthermore, this home-based exergame solution could overcome identified barriers to exercise, such as lack of time, limited access to facilities and appropriate equipment, bad weather, and lack of motivation [4,5], and thus increase the activity level of physically inactive people [47,50]. Nevertheless, further extensions and variety of the exergame might help to maintain motivation as well as the training load at an optimal level over longer training periods in players using the system at home [25].

On-Body Feedback System

The interview data revealed that participants enjoyed the experience with the on-body feedback system. The haptic feedback, in particular, was well received as a single stimulus as well as in combination with the visual feedback. This is in line with findings from previous studies in exergames, which showed that haptic feedback positively influences the feelings of spatial presence, immersion, flow, and motivation [21,51,52] as well as embodiment [53].

Similar to other studies, it could be shown that haptic stimuli in exergames are preferred over auditory and visual feedback [54,55]. In our study, this might also be amplified by the fact that the visual and auditory processing loads were already quite high because of the new information from the virtual game scenario, and thus players had more resources for the haptic feedback. Therefore, the cognitive resources for the auditory and visual feedback remain limited, at least during the first gaming sessions. It can be assumed that this will change after several gaming sessions are completed.

Generally, the features of the newly designed on-body feedback system are very promising. However, the study provided inspiring avenues for further development of the on-body feedback system. Auditory feedback, for example, needs to be

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further optimized since there are specific requirements for auditory feedback and music in sports [56] and exergames [21].

In future research, it would be interesting to evaluate the impact of the different on-body feedbacks on the feelings of empowerment [57] and self-esteem [55] as well as on aspects of movement quality [58].

Limitations

A limitation of this study is the lack of variability in the sample; as the sample within this study was all young healthy participants with a small range in age (19-30 years), the inclusion of a wider age range within this study would have increased the generalizability of the findings. Moreover, there was no defined washout period between the visits, meaning that participants had different time periods between visits 1 and 2. However, no participant had more than 2 weeks between visits; therefore familiarization was similar across all participants.

Conclusions

Overall, the results showed that the home-based exergame and its early-stage on-body feedback system were rated as usable and an enjoyable training experience by a young healthy population. Results demonstrated that this exergame and its on-body feedback system have the potential to be an attractive home-based training solution. Furthermore, avenues emerged for future design iterations of the home-based exergame system. Future studies are needed to investigate the feasibility of the exergame in physically inactive people, assess participants' experiences of repeated home-based use of the exergame, and examine preliminary training effects on physical and cognitive functions in young adults.

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Conflicts of Interest

Besides their academic careers, ALM-N and AS are also working for Sphery. ALM-N is a cofounder of the start-up company Sphery Ltd, which developed the ExerCube based on the results of her previous research projects. AS has been working as Senior Research and Development Manager at Sphery since November 2019. SN is also a cofounder of Sphery, while YR started working as a Project Manager at Sphery in 2021. The remaining authors have no conflicts of interest to declare. No revenue was paid (or promised to be paid) directly to ALM-N, to AS, to SN, to YR, to Sphery, or to the research institutions.

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Abbreviations

Exergame: exercise game
FSS: Flow Short Scale
HR: heart rate
IEQ: Immersive Experience Questionnaire
PACES: Physical Activity Enjoyment Scale
SUS: System Usability Scale

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Original Paper

Immersive Virtual Reality Avatars for Embodiment Illusions in People With Mild to Borderline Intellectual Disability: User-Centered Development and Feasibility Study

Simon Langener[1,2,3], MSc; Randy Klaassen[1], PhD; Joanne VanDerNagel[1,2,3], MD, PhD; Dirk Heylen[1], PhD

[1]Department of Human Media Interaction, University of Twente, Enschede, Netherlands
[2]Centre for Addiction and Intellectual Disability, Tactus Addiction Care, Enschede, Netherlands
[3]Nijmegen Institute for Scientist-Practitioners in Addiction, Radboud University, Nijmegen, Netherlands

Corresponding Author:
Simon Langener, MSc
Department of Human Media Interaction
University of Twente
PO Box 217
Enschede, 7500 AE
Netherlands
Phone: 31 534898771
Email: s.langener@utwente.nl

Abstract

Background: Immersive virtual reality (IVR) has been investigated as a tool for treating psychiatric conditions. In particular, the practical nature of IVR, by offering a doing instead of talking approach, could support people who do not benefit from existing treatments. Hence, people with mild to borderline intellectual disability (MBID; IQ=50-85) might profit particularly from IVR therapies, for instance, to circumvent issues in understanding relevant concepts and interrelations. In this context, immersing the user into a virtual body (ie, avatar) appears promising for enhancing learning (eg, by changing perspectives) and usability (eg, natural interactions). However, design requirements, immersion procedures, and proof of concept of such embodiment illusion (ie, substituting the real body with a virtual one) have not been explored in this group.

Objective: Our study aimed to establish design guidelines for IVR embodiment illusions in people with MBID. We explored 3 factors to induce the illusion, by testing the avatar's appearance, locomotion using IVR controllers, and virtual object manipulation. Furthermore, we report on the feasibility to induce the embodiment illusion and provide procedural guidance.

Methods: We conducted a user-centered study with 29 end users in care facilities, to investigate the avatar's appearance, controller-based locomotion (ie, teleport, joystick, or hybrid), and object manipulation. Overall, 3 iterations were conducted using semistructured interviews to explore design factors to induce embodiment illusions in our group. To further understand the influence of interactions on the illusion, we measured the sense of embodiment (SoE) during 5 interaction tasks.

Results: IVR embodiment illusions can be induced in adults with MBID. To induce the illusion, having a high degree of control over the body outweighed avatar customization, despite the participants' desire to replicate their own body image. Similarly, the highest SoE was measured during object manipulation tasks, which required a combination of (virtual) locomotion and object manipulation behavior. Notably, interactions that are implausible (eg, teleport and occlusions when grabbing) showed a negative influence on SoE. In contrast, implementing artificial interaction aids into the IVR avatar's hands (ie, for user interfaces) did not diminish the illusion, presuming that the control was unimpaired. Nonetheless, embodiment illusions showed a tedious and complex need for (control) habituation (eg, motion sickness), possibly hindering uptake in practice.

Conclusions: Balancing the embodiment immersion by focusing on interaction habituation (eg, controller-based locomotion) and lowering customization effort seems crucial to achieve both high SoE and usability for people with MBID. Hence, future studies should investigate the requirements for natural IVR avatar interactions by using multisensory integrations for the virtual body (eg, animations, physics-based collision, and touch) and other interaction techniques (eg, hand tracking and redirected walking). In addition, procedures and use for learning should be explored for tailored mental health therapies in people with MBID.

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KEYWORDS

virtual reality; VR; embodiment; avatar; embodied learning; body-centered; intellectual disability; addiction; user-centered design

Introduction

Background

Immersive virtual reality (IVR) has been investigated as a treatment tool for a variety of psychiatric disorders, for instance, in people with psychosis, addictive disorders, and eating disorders [1,2]. However, so far, the clinical effectiveness has only been proven in anxiety disorders, as (randomized) controlled trials in other mental illnesses are still required. However, the practical nature as *doing instead of talking* approach makes IVR therapy appealing for people who do not profit from existing treatments, such as people with mild to borderline intellectual disability (MBID; IQ=50-85). People with MBID constitute a diverse group with low intellectual and adaptive capabilities (eg, problems in planning, problem solving, abstract thinking, and judgment), which negatively affects the development of essential skills for independent living. By using the term MBID, we combine the groups mild intellectual disability (IQ=50-69) and borderline intellectual functioning (IQ=70-85), as they often encounter similar challenges in life, for instance, regarding mental health treatments [3-5]. Previous studies suggest that IVR could help to reduce learning barriers, by making abstract concepts and interrelations graspable [6-8], bypassing the need for a disembedded thinking [9]. In addition, IVR for the MBID group could transfer tangible content for an active rather than passive learning [10], thus evading the need for excessive language use and fostering skill acquisition by making mistakes [9]. However, applications of IVR and knowledge about requirements in MBID remain low [11], as few researchers have explored the interaction design using state-of-the-art hardware [12-15]. However, turning with one's own body and interacting via hand-based manipulations were found to benefit usability. Hence, implementing interaction techniques that provide a user experience similar to that of real life seems vital, for instance, by immersion into a virtual body. This *embodiment illusion* could facilitate life-like behavior and therefore improve the access to IVR for our group [16].

Embodiment illusions in IVR allow us to substitute the real body with a virtual body or certain body parts, such as arms or hands [17-19]. The phenomenon is often assessed by the *sense of embodiment* (SoE) toward the virtual body (ie, *avatar*) [19,20]. The "SoE toward a body B is the sense that emerges when B's properties are processed as if they were the properties of one's own biological body." (p375) [19]. Hence, the embodiment illusion is induced through 3 main factors: sense of self-location, agency, and ownership [19,21]. The *sense of self-location* refers to the feeling of being inside the body [19]; the *sense of agency* comprises the "global motor control, including the subjective experience of action, control, intention, motor selection and the conscious experience of will" (p7) [22]; and the *sense of body ownership* involves the self-attribution to the avatar [19]. However, so far, the significance of each factor for the illusion remains ambiguous [19]. Nonetheless, illusions of virtual body ownership (IVBO) were found to influence the user's attitudes and behavior [23], which makes them promising for enhancing therapy outcomes in groups that hardly benefit from cognitively demanding paradigms, such as people with MBID.

Previous findings in people devoid of MBID showed that embodying a Black avatar can reduce racial bias and that embodying a child can influence implicit attitudes and object size perception in IVR [24,25]. Both refer to the *proteus effect*, derived from the Greek myth of a *shape shifter*, describing the phenomenon that we (humans) tend to change our beliefs and behavior based on our (digital) self-representations [16]. For instance, as empathy training, body swapping was used to present power relationships between offender and victim in sexual harassment, subsequently reducing conformity in social pressure scenarios [26]. In addition to such implicit approaches, explicit learning could be applied, for instance, psychomotor addiction therapy with a focus on bodily signals (eg, cravings) [7], by using the virtual body as a multimodal feedback system. However, despite various studies that report on the design requirements for such IVBO, no study has focused on people with MBID. Hence, this study aimed to design IVR avatars for embodiment illusions in individuals with MBID. As the spatial immersion into the IVR avatar and implementation of plausible actions (eg, controls) can evoke realistic behaviors [16], we decided to look into three important components for embodiment illusions: (1) avatar appearance, (2) controller-based locomotion, and (3) object manipulation.

Related Studies

Overview

In the following sections, we examine related studies concerning (1) avatar immersion, (2) controller-based locomotion, and (3) object manipulation. Given the lack of studies in our target group, we report on the existing evidence in non-MBID samples to identify crucial factors for our initial prototype and immersion design. We conclude the *Introduction* section with a summary of potential benefits and barriers of embodiment illusions for people with MBID and our research questions. Then, we describe our user-centered design method with 3 iterations and report the results per iteration. Subsequently, we discuss relevant factors in the context of previous studies, limitations, and directions for future research. Finally, we conclude our paper with a summary of our contribution to the field.

Immersion Into IVR Avatars for IVBO

Several factors contributing to IVR avatar immersion have been investigated to influence SoE, such as the point of view (POV; ie, the perspective), body appearance, control, and haptics (ie, the experience of touch) [19]. For instance, an egocentric POV has been shown to reliably induce the *sense of self-location* [27], whereas a third-person perspective tends to lower it [28,29]. The *sense of agency* is induced through the experienced control of the virtual body [19], influenced by the visuomotor congruence between the real body and avatar [30-32], whereas incongruences tend to lower it [33,34]. Finally, the *sense of ownership* is influenced by body appearance and has been

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induced through avatar models with different degrees of anthropomorphism [35]. However, despite the possibilities to feel ownership toward avatars that differ from oneself in terms of gender and morphological characteristics [36,37], matching gender, skin tone, and clothes can boost IVBO [38,39]. However, the SoE factors cannot be considered to be isolated from each other, as interrelations have been identified [40], such as influence of appearance on agency [41] and control and haptics on ownership [42-44]. Here, recent findings showed that primarily visuoproprioceptive congruence contributes to the *sense of agency* and *ownership* and better task performance [32]. Moreover, Fribourg et al [40] explored the user preferences for 3 vital factors (ie, POV, control, and appearance), showing the need for an egocentric perspective and high motor control to outweigh the avatar's appearance. However, these findings seemed to be task dependent, with POV being relevant for locomotion and avatar appearance when manipulating (virtual) objects using the upper body [40,41,45].

Controller-Based Locomotion for IVR Avatars

Controller-based locomotion, as an essential component of immersion into IVR avatars, can be divided into physical and artificial approaches [46]. Physical techniques can be more intuitive (ie, room scale); however, an intensive bodily involvement and unnaturalness (eg, walking in place) may cause the opposite effect. In contrast, artificial techniques (eg, teleport and joystick) tend to increase the cognitive workload and are prone to cause cybersickness (ie, motion sickness) [46,47]. As space for natural locomotion is often limited, adding artificial techniques of continuous (eg, controller-based) or noncontinuous (eg, teleport-based) nature could form a viable solution [13]. Continuous approaches are preferred in open settings, whereas noncontinuous approaches are widely used owing to their user-friendliness [46]. However, few studies have explored virtual locomotion in combination with IVR avatars, showing its influences on task performance and obstacle avoidance [48-50]. The virtual body can improve walking behavior in IVR, with fewer collisions, more precise paths using a realistic avatar [51], and more natural behavior [52]. Here, using walking animations that mimicked natural behavior were preferred over the user's real motions (ie, walking in place); however, this could lead to unintended steps [53]. Nevertheless, few studies have examined the effects of virtual locomotion on the SoE factors. Dewez et al [50] compared natural walking, walking in place, and virtual steering and found a similar SoE, with equal performance with or without an avatar. Consistent with previous findings, movement incongruences between the user and avatar animation did not break the embodiment illusion [28].

Object Interaction for IVR Avatars

Similar to avatar immersion and locomotion design, interacting with objects and user interfaces (UIs) are essential components for immersive self-representations. Here, using avatars influences the interaction with objects and vice versa [45]. The alignment of this reciprocity to design for both high SoE and usability remains understudied in the current literature, especially when combined with artificial locomotion. Previous studies that used IVR avatars during interaction tasks reported performance enhancements over controllers or virtual hands [54], independent of the model's human-likeness, when comparing a realistic avatar with a generic or robot appearance [55,56]. However, as spatial biases were found in IVR [57], the body may operate as a reference frame [58], as the object size perception can be altered when using avatars [59]. Here, avatars can produce occlusions during interactions, which can affect the usability negatively, especially when using more anthropomorphic models [41,60]. However, using congruent body feedback could circumvent this issue, considering that haptics (eg, self-touch) benefits SoE and manipulation performance [32,61,62]. Finally, identified usability barriers are objects that are out of reach or placed low. A solution devoid of altering the avatar or breaking the embodiment illusion could be artificial interactions (eg, raycasting) implemented into the avatar's hands [45,63], allowing interaction with objects without substantial bodily movements.

Goal of This Study

In summary, embodying an IVR avatar may improve usability [51], spatial awareness [6,45], and (self) presence [31,64]; however, adverse effects can occur owing to an increase in complexity [60]. Nonetheless, so far, design requirements for such IVR avatars and the feasibility to induce IVBO have not been explored in people with MBID. Despite the proposed use for the treatment of psychiatric disorders, IVR applications focusing on life skills (eg, public transport and grocery shopping) [12,13], vocational training [65], and (motor) rehabilitation for MBID could be beneficial [14,66]. The virtual body may reduce the cognitive workload and enables novel forms of visuomotor feedback, for instance, to support the problematic hand-eye coordination of individuals with intellectual disability in IVR [67]. So far, IVBO was mostly investigated in controlled laboratory settings with motion-capture systems or several body trackers to congruently map the user's bodily movements onto the virtual body. Although these systems seem to provide the highest control, they lack consumer-friendliness to enter care institutions, given the high costs and difficulty in using the equipment. Here, solutions based on inverse kinematics (IK) that use 3-point tracking of the head-mounted display (HMD) and related controllers could provide an alternative, as most interactions focus on the upper body [40]. Hence, we aimed to explore guidelines for such IVBO in people with MBID, by conducting a user-centered development based on three factors that contribute to functional and plausible actions [16]:

1. How to design IVR avatars for IVBO in people with MBID?
   a. How to design a virtual embodiment illusion for people with MBID based on IK?
   b. How to design a controller-based locomotion technique for people with MBID?
   c. How to design a controller-based (object) manipulation for people with MBID?
2. To what extent do participants experience SoE during the examined interaction task?
3. To what extent do participants experience a sense of presence (SoP) in the immersive virtual environment (IVE)?

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Methods

Research Design

We conducted a user-centered design approach to explore the 3 factors for IVR avatar immersion (ie, avatar, controller-based locomotion, and manipulation), initial feasibility of procedures, and proof of concept of IVBO in people with MBID. For this, we developed an IVR avatar prototype to identify design recommendations for IVBO using 3 consecutive iterations with end users in Dutch care facilities. Throughout these iterations, we refined the IVR avatar system and immersion procedure according to the participants' needs. Hence, in this study, we established design recommendations for the 3 components and explored the SoE levels and SoP in the IVE to support others in creating accessible IVR avatars.

Participants

In total, 29 adults with MBID were recruited through convenience sampling by local therapists from an addiction clinic for individuals with MBID and Dutch care facility for people with MBID. Exclusion criteria included having a history of migraine, epilepsy, visual or motor impairment, or severe mental disorder (eg, schizophrenia, psychosis, or active substance use disorder); susceptibility to COVID-19; proneness to motion sickness; or inability to wear the HMD.

Interaction System

We built the interaction system with consumer hardware and available software. The game engine Unity3D (version 2019.4 LTS; Unity Technologies) was used with the Mecanim IK and the eXtended Reality interaction toolkit (preview; version 0.94) packages to develop an IVBO based on 3-point tracking of the HMD and the related 2 controllers. We implemented the three identified components for IVR avatars: (1) customizable avatar, (2) controller-based locomotion, and (3) object manipulation.

The customizable IVR avatar component (Figure 1) included an egocentric embodiment illusion. The participants were able to enter their height and arm dimensions (ie, by going into the T-pose), customize their gender (woman or man), and select a skin tone.

The controller-based locomotion component (Figure 2) involved a visuomotor experience of moving in the IVE, divided into physical and artificial approaches. The physical approach comprised basic room-scale locomotion (2×2 m), with walking animation when moving. Overall, 3 artificial locomotion approaches were implemented — divided into joystick locomotion with 45° snap turn and walking animation, teleportation locomotion using raycasting with a projectile curve, and a combination of both (hybrid). Haptics were used at the beginning and when executing teleportation by using the controller's vibration motors. Furthermore, a *teleport travel* technique that enables the transition to the different interaction contexts by using a screen-space UI was implemented [68], which followed the user's rotation on the y-axis when holding the A button.

The (object) manipulation component (Figure 3) included a synchronous visuomotor experience to grab, pick up from low areas, place, and throw virtual objects. We used hand animations for grabbing (grip button) and pinching (trigger button), including haptics, when grabbing and releasing the objects by using the controller's vibration motors. Raycasting on both hands was implemented to pick up objects that are placed low or out of reach and interact with UIs.

Figure 1. The customizable immersive virtual reality avatar: (A) egocentric perspective, (B) raycast interaction with user interface, (C) customization of body dimensions, and (D) touching the nondominant hand with the dominant one.

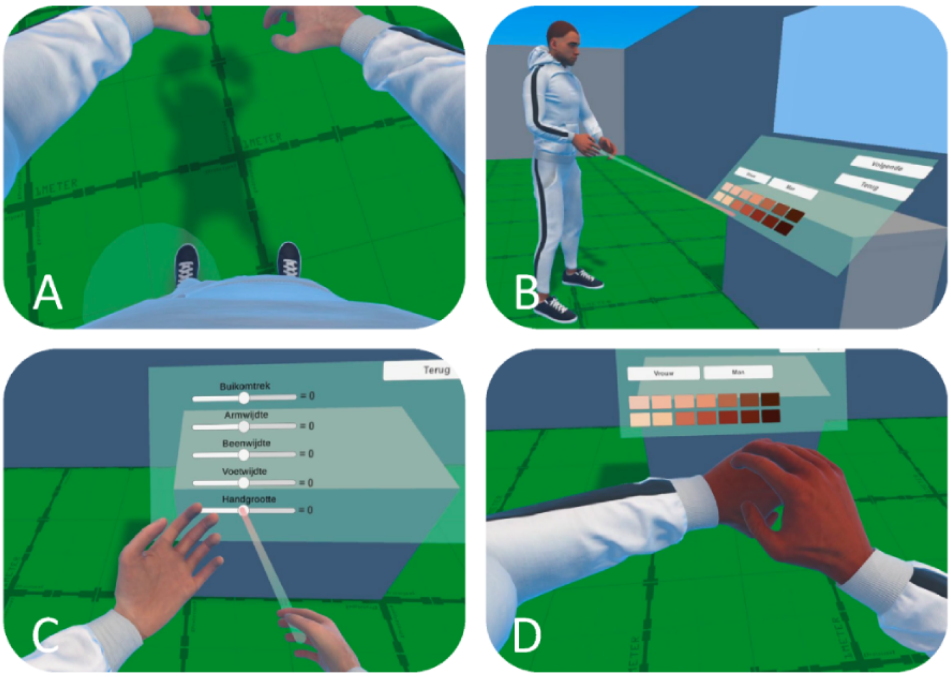

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Figure 2. The controller-based locomotion: (A) joystick locomotion with walking animation, (B) teleportation locomotion using raycasting with a projectile curve, (C) hybrid locomotion (A+B), and (D) teleport travel to interaction tasks.

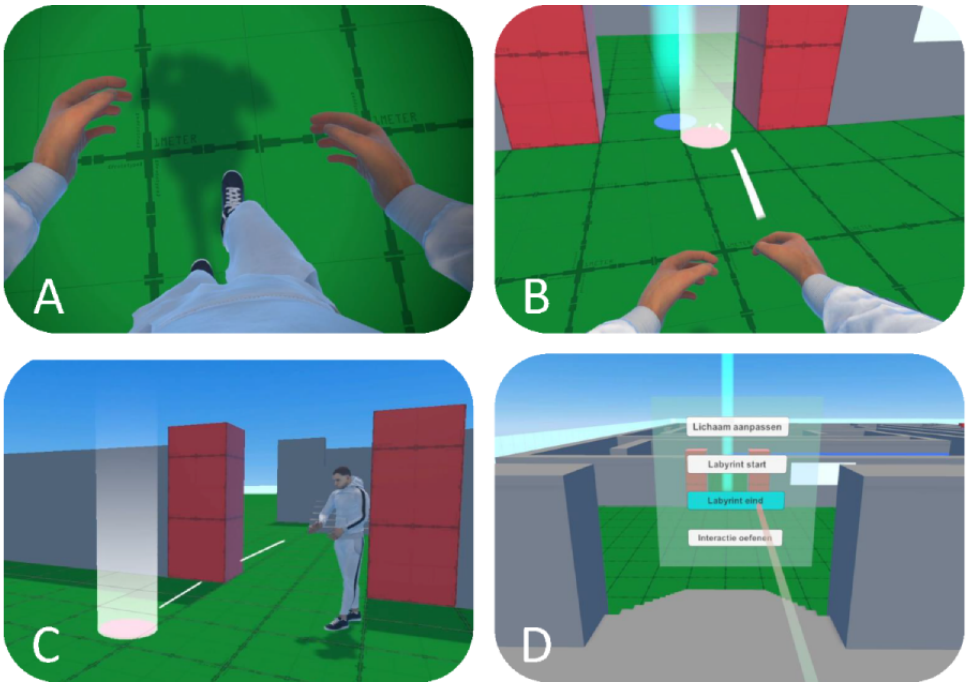
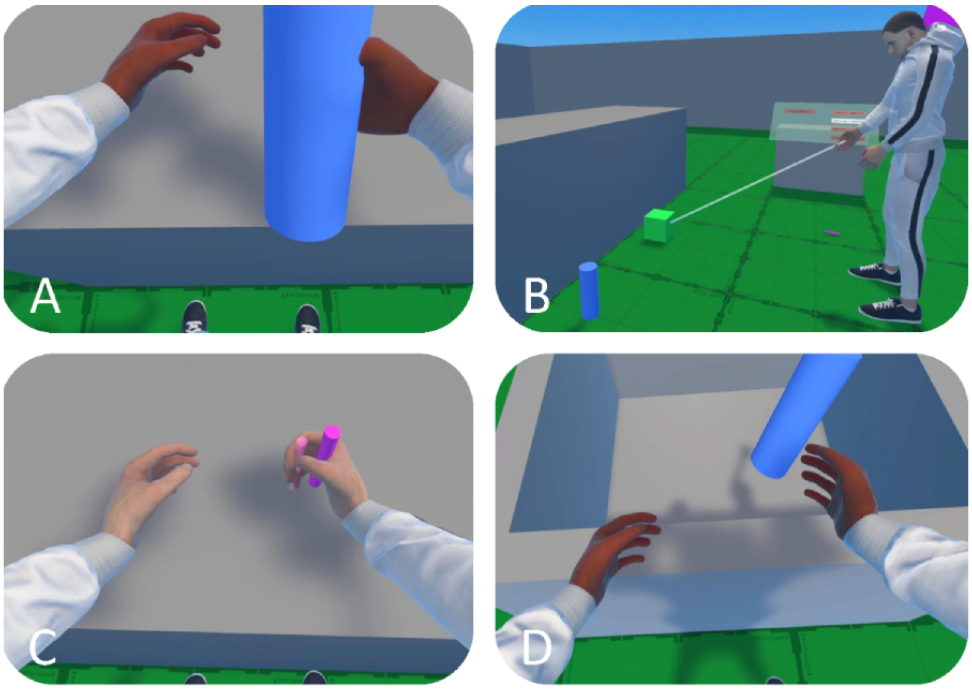


Figure 3. The controller-based object manipulation (A) grabbing objects on the "table", (B) picking-up objects using sphere-casting, (C) placement of objects at cued locations, and (D) throwing objects into a box.



Hardware and IVE

We used an Oculus Quest HMD with 6 df, 1440×1600 pixels per eye, 72 Hz refresh rate, and 90° field of view (FOV); touch controllers; and a compatible IVR-laptop (Intel Core i7 9750H central processing unit; 16 GB RAM; NVIDIA GeForce RTX 2060) with Oculus Link (beta; USB 3.1 cable).

The IVE encompassed an open-world mechanic (200×200 m) to evaluate the system's components. In the first room setting (15×15×2.5 m), the participants customized the IVR avatar. In the second room, artificial locomotion techniques were evaluated by completing a maze (50×50×2.3 m) with 4 destinations and obstacles to provoke different user movements. On the basis of common game design, we used a vantage point to support spatial understanding and reduce unease. Further, destinations were cued using light beams of different color, with matching leading lines on the walls [69]. In the third context (15×15×2.5 m), we evaluated 4 basic object manipulation tasks to ensure a broad coverage of possible IVR interactions. For this, we used 3 different objects (ie, large cylinder, cube, and small cylinder) to grab and release each object (Figure 3A), pick up the object from the ground (Figure 3B), place objects at another location

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(Figure 3C), and throw all objects into a box (Figure 3D). The corresponding task completion was detected by the system automatically (eg, object grabbed and released), allowing users to transition to the next task. Participants used object-spaced UIs with low hierarchy to customize the avatar, select locomotion approaches, and control interaction tasks. A plain design was used to reduce bias, and we implemented landmarks (pink in color) to aid user's orientation in the IVE.

Measures

A semistructured interview (Multimedia Appendix 1) was conducted after each of the 5 interaction tasks: IVR avatar customization, teleport, joystick, hybrid locomotion, and object manipulation. For the IVR avatar, we aimed to explore the first impression, customization choices, usability issues, ownership perception, and points for improvement. For locomotion, we explored the first impression, usability issues, and impression of the body during locomotion. The questions for all locomotion techniques were identical. Regarding object manipulation, we asked for the first impression, usability issues, enjoyable aspects, and perception of the body during interaction. Finally, we evaluated the impressions and usability issues concerning IVE, UI interactions, and intentions for using the system.

SoE was assessed using an adapted version of the Virtual Embodiment Questionnaire (VEQ) [20]. The VEQ is a 12-item questionnaire assessing the SoE subscales ownership (Cronbach α=.78), agency (Cronbach α=.76), and change (Cronbach α=.77). In addition, 3-items assessing the sense of self-location were adapted to this research context to extend VEQ [21,30]. Scores for each item ranged from 1 ("strongly disagree") to 7 ("strongly agree").

SoP was assessed using an adapted version of the Igroup Presence Questionnaire (IPQ) [70]. The IPQ (Cronbach α=.85) is a 14-item questionnaire assessing the SoP subscales general presence, spatial presence (Cronbach α=.80), involvement (Cronbach α=.76), and experienced realism (Cronbach α=.68). Scores for each item ranged from 1 ("strongly disagree") to 7 ("strongly agree").

Considering the needs of people with MBID, we adapted questionnaires in language and complexity (by using plain Dutch language) with an expert from the field. This implies that questions asking for 2 different concepts were reduced to one; for example, "I felt like the form or appearance of my own body had changed" was changed to "I felt like the form of my own body had changed" [20]. In addition, complex formulations were simplified; for example, "Somehow I felt that the virtual world surrounded me" was changed to "I felt that the virtual world surrounded me" [70].

Ethics Approval

Ethics approval was obtained from the University of Twente's ethics committee (RP 2020-164) and the care institution's scientific board.

Procedure

To comply with COVID-19 precautions, the researcher disinfected the materials and IVR apparatus before evaluation. Before evaluation, disinfection of hands and forearms was required, a medical mask was used by the researcher, and a distance of 1.5 m was maintained whenever possible.

Participants were welcomed and informed about the study procedure before starting the experiment to comply with the ethical principles in accordance with the Declaration of Helsinki. The researcher explained the IVR technology, controls, and possible adverse effects. After informed consent was obtained, the participants were immersed into the IVE. In addition to visual in-game cues, verbal instructions were used to guide the user through the procedure.

Before assessing the prototype version, participants found themselves in the customization room with controller models enabled, but deactivated avatar. First, users were asked to set the interpupillary distance using the HMD slider for proper vision. Then, a short acclimatization period was conducted to enhance spatial understanding, which includes the basic room-scale boundaries and locomotion. After the remaining questions were answered, the assessment of the different components was initiated.

The first task involved avatar customization (Figure 1). Participants were instructed to go into T-pose to conduct the scaling procedure, followed by the selection of gender and skin tone on the UI (Figure 1B), which enabled the avatar (Figure 1A). The participants were given a maximum of 5 minutes to explore the avatar, hand, and walking animations using room-scale locomotion. After approximately 3 minutes, the participants were asked to touch the nondominant hand by using the dominant one to explore the self-location of hands through a tactile sensation (Figure 1D). Then, users were asked to remove the HMD, so that the extended VEQ and dedicated semistructured interview questions can be assessed by the researcher. After completion, participants were asked to wear the HMD again to proceed to the next component.

The second task evaluated the controller-based locomotion techniques to move in the IVE (Figure 2). The participants were asked to *teleport travel* to the vantage point by using the related UI (Figure 2D). Then, participants enabled the predefined locomotion approach, that is, joystick (Figure 2A), teleport (Figure 2B), or hybrid (Figure 2C). Following an introduction to the technique, participants were asked to complete the maze. In case of severe motion sickness, participants were allowed to stop early to complete the remaining procedure. Upon completion, participants were asked to remove the HMD to assess the extended VEQ and corresponding interview questions. Then, end users were asked to wear the HMD again to evaluate the remaining locomotion techniques by following the same procedure in an overall counterbalanced manner.

The third task included different manipulations of 3 objects in a room setting (Figure 3). First, participants were asked to *teleport travel* to the locomotion UI to enable the preferred technique. Then, participants were instructed to *teleport travel* to the manipulation tasks and move to the interactables and related UI. The participants were instructed to (1) grab and release each object (Figure 3A), (2) pick up the object from the ground using raycasting (Figure 3B), (3) place objects at another location based on cues (Figure 3C), and (4) throw objects into a box (Figure 3D). After completion, the participants were again

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asked to remove the HMD and the extended VEQ and related interview questions were assessed.

Following the evaluation of the 3 avatar components, participants were asked to provide demographic information and to complete the IPQ and remaining interview questions. Finally, users were debriefed and encouraged to express remaining questions or concerns, and they were subsequently thoroughly answered. The participants received a small nonmonetary gift as a sign of gratitude (approximately €10 [US $10]).

Data Analysis

Qualitative data were analyzed based on the thematic analysis approach by Braun and Clarke [71]. To account for the research design, we divided data sets from the iterations into three segments each: (1) avatar customization, (2) artificial locomotion, and (3) manipulation. In these segments, coding was applied to the data that were transcribed verbatim to identify themes by conducting a recursive process using Atlas.ti (version 9.1.4; ATLAS.ti GmbH). The coding process was continuously discussed among the researchers (ie, SL, JV, and RK). Quantitative data regarding the extended VEQ and IPQ subscales were described for each iteration and on an aggregated level. Descriptive analyses were conducted using RStudio (version 1.3.1093).

Results

Sample Description

Table 1 presents the sociodemographic characteristics and technological experience of the sample. Of the 29 participants, 5 participants (17%) terminated prematurely owing to severe motion sickness (3/5, 60%), anxiety (1/5, 20%), or use inability (1/5, 20%), resulting in missing experimental and demographic data. The remaining participants (24/29, 83%) had a mean age of 34.2 (SD 9.8) years, and most identified as male (23/24, 96%). The sample was equally composed from the 3 institutions (8/24, 33% from each) and included participants with borderline intellectual functioning (IQ=70-85; 13/24, 54%) and mild intellectual disability (IQ=50-69; 11/24, 46%). The technology experience with computers and videogames was rated high compared with virtual reality. The following sections describe the process that led to our final prototype and procedural considerations identified during the design process.

Table 1. Sociodemographic characteristics and technological experience of the sample.

Sample characteristics	Iteration 1 (n=6)	Iteration 2 (n=12)	Iteration 3 (n=6)	Full sample (n=24)
Age (years), mean (SD)	33.83 (9.24)	36 (8.77)	30.83 (12.78)	34.17 (9.77)
Gender, n (%)				
Men	6 (100)	11 (92)	6 (100)	23 (96)
Women	0 (0)	0 (0)	0 (0)	0 (0)
Diverse	0 (0)	1 (8)	0 (0)	1 (4)
Intelligence, n (%)				
Borderline intellectual functioning	3 (50)	6 (50)	4 (67)	13 (54)
Mild intellectual disability	3 (50)	6 (50)	2 (33)	11 (46)
Institution, n (%)				
Addiction clinic	2 (33)	4 (33)	2 (33)	8 (33)
Care institution	2 (33)	4 (33)	2 (33)	8 (33)
Forensic addiction clinic	2 (33)	4 (33)	2 (33)	8 (33)
Technology experience[a], mean (SD)				
Computer	5.83 (0.75)	5.50 (1.38)	5.17 (1.47)	5.50 (1.25)
Video games	4.17 (0.75)	5.83 (1.34)	6.17 (0.98)	5.50 (1.35)
Virtual reality	2.17 (1.47)	3.08 (1.88)	3.33 (2.66)	2.92 (1.98)

[a]Technology experience was assessed using a 7-point Likert scale, ranging from 1 (“No experience”) to 7 (“A lot of experience”).

Iterative Prototype Development

Findings From Iteration 1

Overview

Most participants (4/6, 67%) reported a positive first impression regarding the IVR avatar system. The scaling procedure was feasible; however, visual in-game instructions were lacking. Here, the avatar’s congruence with one’s own self-concept was essential, because users selected their own skin tone and gender, reporting on the desire to replicate their own body image:

> *I’m really a slim puppet now. In real life, I have a bit of a belly.* [Participant 4]

Furthermore, technical issues were described, such as unrealistic wrist movements and arm glitches and the absence of haptics (self-touch) properties:

> *You cannot grasp it, so it is not yours.* [Participant 1]

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Regarding joystick locomotion, participants reported usability issues when using the 45° snap turn, further contributing to the prevalent cybersickness:

> *When you hit the wall, it gets really bad.* [Participant 3]

In contrast, cybersickness was absent during teleport locomotion:

> *The teleporting went better. I did feel better.* [Participant 3]

However, usability issues owing to the limited flexibility and own pace were described:

> *At one point it went too fast. Then it seems too easy, but then you have to take a step back.* [Participant 5]

In contrast to the joystick approach, during teleport use, participants missed the human-like walking illusion:

> *Seems like I just really walk, so to speak.* [Participant 6]

The hybrid approach (ie, joystick and teleport) showed no added value, as participants relied on their preferred technique. However, all approaches showed a need for control habituation and attention shift from avatar to task.

Finally, for (object) manipulation, the usability was rated positively; however, participants reported issues with raycasting, either because it was always enabled or because it was difficult to hit the objects on the ground. Owing to the lack of intuitiveness ("Normally you can bend down and grab." [participant 2]) and haptics, a need for control habituation was essential:

> *Because it feels very different from when you're actually grabbing something.* [Participant 3]

Of the 6 participants, 2 (33%) reported on interaction realism ("But you know, all the movements, the behavior is indeed real." [participant 5]), whereas another participant missed realistic gabbing animations by using the virtual hands instead of the controller. The UI interaction showed good usability, despite the need for repositioning to use the object-spaced UIs.

Changes for Iteration 2

Regarding the IVR avatar, the snap turn was refined from 45° to 15° to remove usability issues and alleviate cybersickness. To improve manipulations, the grabbing attachment was changed to the avatar's hands instead of the controller anchor, and raycast activations were reduced to objects below 50 cm. To enable further customization, alteration of the model's body dimension (size of the arm, belly, leg, and feet) was implemented (Figure 1C). We also improved implementation issues that led to a smaller scaling of the model. Furthermore, we refined the accuracy of the hand IK targets for better proprioception. Finally, as the VEQ items seemed complex for our target group, we added 2 questions to the semistructured interview (Multimedia Appendix 1), asking for the sense of ownership after each interaction task and the perception of change after the evaluation procedure.

Findings From Iteration 2

Overview

Accordant with the first iteration, replicating one's own body image was paramount, self-touch and physical collision were lacking, and some animation issues (ie, arm glitches and unrealistic leg movements) were reported. In contrast, participants reported on the clothing, either owing to the incongruence ("Because the suit I was wearing didn't match with what I was wearing." [participant 15]) or illusion of wearing the virtual clothes ("I was really convinced in my head, that I was wearing it today." [participant 10]). Technical issues included a restricted view toward the lower body when bending ("When I look down like that, all of a sudden, I got a belly." [participant 9]), which also hindered customization owing to occlusion. Moreover, hand size adjustments and customization aids (ie, presets) were lacking. Notably, the human-likeness was described as mostly positive; however, a user missed the haptics and described the uncanny valley:

> *I actually found that a bit creepy. Because your hands actually looked like real hands.* [Participant 10]

Regarding artificial locomotion, cybersickness and snap turn issues remained during joystick walking. Further usability remarks included inaccurate wall collisions with lacking haptics, inaccurate physics (ie, weight), unrealistic foot tilting ("So when I walked fast, my feet just shuffled." [participant 17]), preferences for walking using room scale, and advanced movements (ie, running, jumping, and climbing). As in the previous iteration, participants missed the human-like walking illusion ("I did walk by myself but also didn't." [participant 13]) during teleport ("It was a little inhuman." [participant 19]); however, some participants habituated:

> *At some point when you do figure it out, yes, then it will probably be a little easier.* [Participant 11]

Nonetheless, other usability problems, such as limited range, restricted mobility, fast pace resulting in errors, and activation issues, were described. The required bodily turning was perceived as ambiguous, with a participant suggesting the addition of a snap turn. Consistent with the previous iteration, users relied on their preferred technique for hybrid locomotion, and all techniques showed a need for control habituation and attention shift from body to task.

Finally, manipulation usability was rated positive; however, the need for habituation periods for movements and controls, that is, switching between locomotion and object manipulation, controller assignment ("What is where? A and B, joystick." [participant 8]), and limited room-scale area ("If you had more space, you could just walk there." [participant 9]), were described. As in the first iteration, hitting objects with raycasting was troublesome. Furthermore, a participant reported on missing haptics:

> *On the one hand, it feels very familiar and on the other, it's unrealistic that I don't feel.* [Participant 10]

Here, half of the participants (6/12, 50%) described the interactions as realistic; however, few participants mentioned

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the lack of grabbing realism and unrealistic physics or collision resulting in occlusion. Despite needing habituation, all participants (12/12, 100%) reported good usability regarding the UIs.

Changes for Iteration 3

For the third iteration, we simulated bending using backward placement of the virtual body, aiming to increase the visuoproprioceptive congruence for more natural behavior. Furthermore, we refined the accuracy of the IK targets and improved the smoothness of the body rotation, by including influences of the hand locations. Moreover, we removed arm scaling owing to the preponderant symmetric nature of human bodies and difficult scaling procedures. Notably, we deactivated the HMD's energy saving option, because we discovered floating floor levels after reactivation, which we aimed to account for during the iteration. To improve object manipulation realism and remove usability issues, the *idling* hand animation was refined, and objects were picked up with spherecasts instead of raycasts (ie, *magnetic* toward the object). To allow further customization, we added an option for hand size adjustment to the related UI. Finally, we implemented a dynamic FOV reduction (ie, vignetting) to alleviate cybersickness during artificial locomotion.

Findings From Iteration 3

As in the previous iterations, replicating one's own body image through customization was key. Participants described the avatar as human-like ("It looks real, and I also felt that I was touching my own hand." [participant 24]) with congruent haptics, and 33% (2/6) of the participants justified customization choices (ie, skin tone) in contexts of social meaning:

> *And it's not because I'm racist.* [Participant 24]

Similar to the previous iterations, minor technical issues such as an unrealistic wrist movement and imprecise bending of legs remained.

Regarding joystick locomotion, cybersickness and snap turn issues remained, but were reported to be less severe. Participants rated the embodiment as positive, reporting on the human-like walking illusion; however, a participant described an unrealistic foot tilting. Furthermore, the preference for turning using one's own body, inaccurate wall collision, and attention shift to the task were described. Consistent with the previous iterations, cybersickness was absent during teleport locomotion; however, usability issues owing to the fast pace, activation issues, and turning using one's own body remained:

> *I had to turn but I couldn't walk.* [Participant 22]

In addition, control issues that rotate the user after teleporting were reported. However, the avatar was rated as positive, even though participants described an ambiguous human-likeness when teleporting and attention shift from avatar to task. Accordant with the other iterations, all approaches showed a need for control habituation, and the hybrid locomotion remained mostly unused.

Consistent with the previous iterations, participants reported positive manipulation usability despite the need for initial (control) habituation. Only 17% (1/6) of the participants mentioned selection issues when using the object-spaced UI, whereas another participant preferred the screen-spaced approach over the object-spaced one. Finally, the embodiment during manipulations was rated as positive and human-like, with a participant describing the feeling of haptics through the controller's vibration motors ("When I grabbed something, I also felt a vibration through my hand...It really felt like I was holding something." [participant 19]) and unused artificial locomotion owing to the immersion ("I forgot that I could also walk with my joystick." [participant 19]).

SoE Related to IVR Avatar Task

Table 2 shows the extended VEQ scores throughout our iterative development. The contextual differences indicate that the sense of ownership tends to increase with growing interaction capabilities, whereas the perception of change (in the perceived body schema) decreases. In contrast, the sense of self-location and agency scores remained relatively stable across measurements, with positive agency trends during interactions, whereas self-location feelings decreased. Interestingly, ownership and agency scores regarding teleport locomotion were lower than those in other active contexts, which matches the qualitative data.

The qualitative data indicate that IVBO was dependent on habituation ("Just a matter of getting used to it." [participant 3]), sense of agency ("He does what you do, so to speak." [participant 5]), self-location ("Because you are controlling that body, so you are looking at it from the eyes of the virtual person." [participant 15]), customization ("Because I just chose the same that I am." [participant 3]), human-likeness, and haptics ("It looks real, and I also felt that I was touching my own hand." [participant 24]). Throughout the iterations, ownership perceptions ranged from overall heterogenous to mostly positive; however, some participants remained ambivalent:

> *...Because I still know this in my real body and not that.* [Participant 20]

Regarding the teleport locomotion, participants reported heterogenous ownership feelings, illustrated by unrealistic movements and low agency, with a participant questioning the self-location after teleporting:

> *...Because you move forward so quickly I thought: "Will that body come with me."* [Participant 19]

In contrast, joystick locomotion showed mostly positive ownership remarks, illustrated by the human-like movement illusions and agency through controller operation:

> *The movements I made with the joysticks, it made those too.* [Participant 5]

Furthermore, object manipulations showed positive ownership remarks owing to the gain of agency, manipulation realism, and human-likeness. In contrast, the perception of change decreased throughout the iterations. Although some participants in the second iteration felt lighter, smaller, or taller ("I was tall anyway, but I felt even taller when I was there in that game." [participant 14]), participants in the third iteration reported only minor remarks ("My body just felt the same all the time."

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[participant 20]). Notably, some participants disliked embodying an incongruent avatar ("I don't want to be someone else." [participant 18]), for example, in contexts of social interactions:

Because I think it's important that I don't mislead people. [Participant 15]

Table 2. Extended Virtual Embodiment Questionnaire scores (sense of embodiment) related to iteration and task.

Context	Avatar customization, mean (SD)	Teleport locomotion, mean (SD)	Joystick locomotion, mean (SD)	Hybrid locomotion, mean (SD)	Object interaction, mean (SD)
Sense of ownership					
Iteration 1	4.08 (1.69)	4.75 (2.41)	4.92 (2.04)	5.46 (2.28)	5.25 (2.32)
Iteration 2	5.15 (1.32)	4.83 (1.24)	5.62 (1.07)	5.81 (0.82)	5.96 (1)
Iteration 3	4.29 (1.16)	4.17 (1.72)	5.92 (1.19)	5.21 (1.44)	6.21 (0.95)
Overall	4.67 (1.41)	4.65 (1.65)	5.52 (1.38)	5.57 (1.40)	5.84 (1.41)
Sense of agency					
Iteration 1	5.71 (0.75)	5.71 (2.14)	6.08 (0.61)	5.96 (1.09)	5.96 (1.50)
Iteration 2	6 (1.19)	5.23 (1.35)	6.17 (0.86)	6.02 (0.98)	6.15 (1.01)
Iteration 3	5.67 (1.24)	5.46 (1.49)	5.96 (1.10)	5.38 (1.81)	6.38 (0.89)
Overall	5.84 (1.08)	5.41 (1.55)	6.09 (0.84)	5.84 (1.23)	6.16 (1.08)
Change (in the perceived body schema)					
Iteration 1	5 (1.59)	3.75 (2.24)	3.38 (2.22)	3.79 (2.33)	3.08 (2.78)
Iteration 2	3.65 (1.32)	3.06 (1.45)	3.42 (1.54)	2.85 (1.54)	2.56 (1.20)
Iteration 3	3.75 (1.69)	3 (1.74)	3.42 (2.06)	3.17 (2.08)	3.33 (2.04)
Overall	4.01 (1.53)	3.22 (1.69)	3.41 (1.77)	3.17 (1.84)	2.89 (1.84)
Sense of self-location					
Iteration 1	6.56 (0.66)	5.83 (1.01)	5.50 (1.66)	5.56 (2.33)	5.83 (1.76)
Iteration 2	6.44 (0.59)	6.22 (0.78)	6.14 (0.77)	6.42 (0.61)	6.22 (0.96)
Iteration 3	5.67 (0.97)	5.06 (1.83)	5.56 (1.03)	4.94 (1.85)	5.94 (1.04)
Overall	6.28 (0.77)	5.83 (1.22)	5.83 (1.10)	5.83 (1.58)	6.06 (1.17)

Locomotion Preferences and SoP

Most participants described a preference for joystick locomotion (15/24, 63%). Few participants selected the hybrid (5/24, 21%) or teleport locomotion (4/24, 17%). The latter was predominantly chosen by users who had experienced (severe) cybersickness. However, the dropouts (5/29, 17%) did not indicate their preference, which should be considered carefully.

The general presence (mean 6.12, SD 0.90) and spatial presence (mean 6.03, SD 0.81) were rated high compared with moderate involvement (mean 4.27, SD 1.88) and low realism (mean 3.59, SD 1.38) scores. The IVR environment was often described as unrealistic and boring; hence, participants suggested improving the graphics and realism, including some agents, objects (eg, chair, cars, and plants), or games, to make the experience more appealing. However, according to participant 11, this may cause overstimulation and distress.

Discussion

Principal Findings

This study reports on the feasibility and related design guidelines for IVBO in adults with MBID, by conducting a user-centered design approach with 3 iterations. In contrast to previous studies on IVR embodiment illusions, our avatar was tailored to the needs of our vulnerable group, by gradually adding interaction and customization abilities. In particular, we investigated the IVR avatar with related IK, controller-based locomotion, and (object) manipulation (Multimedia Appendix 2 [7,19,38,39,45,46,52,72,73]).

In the following sections, we discuss the findings related to our research questions. First, we discuss the feasibility to induce the illusion, influence of interactions on SoE, and guidance to enhance the immersion. Then, we discuss the design insights from our three IVR avatar components: (1) avatar appearance, (2) controller-based locomotion, and (3) object manipulation. Finally, we report on the limitations of our study, provide guidance for future studies, and provide a succinct summary of our contribution.

Immersing People With MBID Into IVR Avatars

Our findings indicate that adults with MBID can embody anthropomorphistic IVR avatars from an egocentric perspective [27], even when avatar dimensions slightly differ from the self [24]. As expected, the highest ownership scores were achieved during object manipulation, requiring the amalgamation of interaction and navigation; however, adding locomotion that mimicked human walking was sufficient to enhance the IVBO

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compared with baseline [50]. Despite the participants' desire to replicate their own body image through customization, this did not lead to effectual IVBO using our IVR. In contrast, adding body control was found to be decisive, suggesting that the sense of agency is vital for inducing ownership illusions in people with MBID [74-76]. This finding is further supported by a decreasing perception of change in the body schema during more extensive interactions, despite the unaltered avatar dimensions. However, the obtained sense of agency and self-location scores showed variance in active contexts, possibly owing to visuomotor incongruences or missing human-likeness during locomotion [28,50], occlusions during interaction [45], and extended insights into the limitations of the IK. Hence, we suggest further multisensory integrations [77], that is, advanced IK, animations, and physical interactions (eg, collision) with haptics to amplify the illusion [44,78]. Moreover, implementing more appealing IVEs could improve user involvement and realism, potentially enhancing IVBO [31,64]. However, using IVR avatars for people with MBID required extensive habituation periods when inducing and ending the IVBO, for example, by gradually adding control and providing support after acclimatization, as some participants described prolonged body sensations:

> *But for my own body I have to get used to it very much. Also when I take off the glasses, all at once bam, oh I'm here huh.* [Participant 9]

This process proved to be time consuming and complex, potentially hindering uptake and usability in practice. However, tailoring the IVR avatar to the user and use may circumvent this issue, allowing to integrate solely essential (and plausible) interactions, while considering user characteristics (eg, short attention and motor coordination issues) for a fitting immersion procedure.

Designing IVR Avatars for People With MBID

The initial IVR avatar was developed based on the relevant literature and comprised models with high anthropomorphism from an egocentric perspective [38,72], customizable gender (man or woman) [73], skin tone [39], and body dimensions (ie, model and arms) [45,52]. In contrast to other studies, we omitted a mirror to inspect the virtual body, given that negative influences on ownership were suggested in previous studies [79]. Our results indicate that extended avatar customization could increase feelings of ownership for people with MBID, given the desire to replicate their own body image, in particular, the body dimensions. However, precise replication methods remain complex and are subject to future studies [39,80], limiting their applicability in consumer settings. However, replication fidelity in our design questions the need for personalization to induce IVBO in our target group. Instead, identification with the virtual body through a customization procedure seemed paramount, by replicating major body image characteristics with generic presets ("I'm really a slim puppet now. In real life I have a bit of a belly." [participant 4]), as used in commercial social IVR applications (eg, Meta Horizon). Here, modifiable features (eg, clothing) appeared more trivial than body image features (eg, gender, skin tone, and corpulence). However, the body as reference frame could affect agency, interaction usability [45], and perception of the world [24,81], possibly resulting in unintended effects [23]. Furthermore, the lack of mirror and plain IVE could have reduced the incongruence awareness in our study [50], as IVR environments can influence perception [57], and facial properties may backfire when not personalized [39]. Nonetheless, our IK system proved sufficient to induce IVBO; however, avoiding impaired control was crucial, as occlusions showed more negative remarks than visual mismatches regarding leg movements [45,50]. Hence, functions for bending should be implemented to achieve sufficient proprioceptive congruence with the user's body.

Designing Controller-Based Locomotion Approaches for People With MBID

We investigated the design and user preferences for artificial IVR avatar locomotion approaches of continuous (ie, joystick) and noncontinuous nature (ie, teleport). Our findings in people with MBID indicate a favor for the joystick in contrast to the teleport or hybrid approach. This difference was explained by the human-likeness and fidelity during joystick locomotion, which can be supported by high ownership and agency values. In contrast to others, we considered user preferences during our design process, used approaches of different nature, and explored the effects on SoE [50]. Accordant with previous studies, natural walking animation was vital [50,53], and visuomotor incongruences between the model and stagnant user did not break the illusion [28,50,82]. Instead, users described a sense of agency via controller operation, which can be supported by the obtained SoE scores. Similar findings were observed in the study by Dewez et al [50], suggesting that control over the IVR avatar is paramount to visual congruence. A potential explanation for this walking illusion may be the user's attention shift toward navigation, which reduces the awareness of visuomotor incongruences while providing a realistic movement illusion. In contrast to the similar SoE levels when comparing continuous techniques in populations that are not impaired [50], we found lower SoE scores when using the noncontinuous teleport. However, the prevalence of cybersickness and the resulting dropouts during joystick locomotion indicate severe usability drawbacks. Hence, designing for cybersickness alleviation seems essential to achieve both high SoE and usability, for instance, through adaptable locomotion. Our findings suggest tailoring FOV (eg, vignetting), turning (eg, snap turn and bodily turning), pace (eg, speed and range), and experience (eg, avoiding collision and stairs) to account for the needs of our group. In addition, enabling control habituation was crucial, given that artificial approaches tend to increase the cognitive workload [46]. Finally, hybrid locomotion was redundant because users relied on their preferred technique. However, it remains interesting to explore this approach in more experienced users, as it allows fast movement without cybersickness, while providing fidelity for object manipulation.

Designing Controller-Based (Object) Manipulations for People With MBID

We further explored the controller-based IVR avatar interaction by allowing users to engage in object manipulation tasks with the customized body and preferred locomotion approach. Here,

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designing for an intuitive interaction was decisive, with realistic animations of virtual hands, physical collisions, and related haptics, further supporting the suggested multisensory integration to enhance IVBOs. Although not implemented in our prototype, tailored hand animations could be used to avoid visual interpenetration with virtual objects [45]. Previous study has shown that users favor defined hand poses [83]; however, constraints through limited animations could reduce SoE and affect performance [45]. For interactions with objects that are placed low, implementing a spherecast that is *magnetic* outperformed raycasting and bending. Although bending was attempted intuitively by our participants, it resulted in severe balance errors that can potentially cause injury. In contrast, raycasting showed severe usability drawbacks for small objects, presumably because the visual and haptic feedback was merely activated when hitting the object. Notably, using artificial interactions did not entail negative remarks, presuming that the control remained unimpaired. Nonetheless, object interaction using full IVBO is understudied, particularly when combined with artificial locomotion. During our design process for people with MBID, we observed usability issues when both were combined. Although control habituation could reduce these issues, providing a generous room-scale area for object manipulation seemed more user-friendly; however, physical walking was limited to 2×2 m. Nonetheless, as space is mostly restricted, we encourage others to further explore the requirements for an unobtrusive amalgamation of interaction and locomotion. Finally, the operation of object-spaced and screen-spaced UIs showed good usability with no negative effects, indicating the potential for autonomous use of such IVR applications by our target users.

Limitations and Future Studies

Our study has some limitations that should be considered. First, our convenience sampling in the design process included mainly male participants with some technology literacy, which may reduce the generalizability of the findings to the diverse group with MBID. Second, we failed to achieve an accurate scaling method in the first 2 iterations owing to technical issues, considering that the state-of-the-art system was still in the beta stage and applied outside the controlled laboratory setting. However, the findings provide valuable insights for our design and hint toward applications of implicit learning (eg, proteus effect) [23], as SoE was observed despite inaccurate avatar dimensions. Third, severe cybersickness issues resulted in dropouts, which may have biased the obtained data, such as locomotion preferences. Fourth, questionnaires were assessed verbally, possibly leading to an increased social desirability bias, whereas paper-based approaches can increase complexity. Previous study from our group suggests that a Visual Analogue Scale implemented in IVR may be more appropriate [7]. Finally, we used a plain IVE that may reduce spatial awareness, such as height and object size perception [24]. Hence, we suggest using spatial cues in future studies, which should be carefully selected to avoid distress (ie, overstimulation) in people with MBID.

Future studies should build upon our findings to further refine our guidelines for IVR avatars for people with MBID to design natural IVR interactions and learning (eg, psychotherapy, health education, and life skills training). Here, influences on SoE should be investigated to evaluate the interaction design and confirm the feasibility of IVBO in diverse samples (eg, technology literacy and intellectual and adaptive functioning). From a technical standpoint, exploring multisensory integrations (eg, advanced IK, interaction animations, haptics, and physics-based manipulations) appears to be paramount to enhance the feeling of agency, as natural and unimpaired interactions seem to be pivotal for IVBO. However, investigating advanced body replication methods as opposed to more generic presets seems to be important to understand the self-attribution to IVR avatars in people with MBID. Our prototyping in the care setting revealed that customization and habituation procedures were complex and tedious, potentially hindering the applicability of IVBO in people with MBID. Hence, using a balanced design by conducting habituation periods (ie, adapting locomotion and interaction) before avatar customization seems promising to reduce the required time for inducing IVBO. This implies neglecting properties that are more trivial in the given use context, such as clothing or facial features, which may be more relevant in social or collaborative IVR. Furthermore, the application of our locomotion and manipulation modules should be investigated with varying degrees of embodiment (eg, full body vs hands) to tailor the interaction design to the individual user and use case. This could reduce the tailoring effort and occurrence of adverse effects (eg, cybersickness), for instance, by limiting locomotion to room scale for body swapping scenarios, whereas public transport trainings may profit from artificial techniques for an extended range. For cueing, using game design and narratives seems promising, as common visual interaction cues (eg, light beams, leading lines, and placement cues) and aids (eg, vantage points and landmarks) showed adequate usability. Finally, we combined promising design components; however, a plethora of other interaction techniques can be explored, such as redirected walking to further alleviate cybersickness.

Conclusions

Our findings suggest that adults with MBID can embody gender-matched IVR avatars with high anthropomorphism. To induce IVBO, having a high sense of agency over the virtual body appeared to be crucial, ideally with corresponding multisensory feedback, such as physics-based collisions and haptics. This is consistent with previous studies on place illusion and plausibility illusion [16], suggesting that plausible interactions are vital for IVBO in our group. However, implementing artificial aids into the virtual body (ie, spherecasting and raycasting) was not perceived as disruptive, presuming that the control was not impaired. Customizing the avatar according to the participant's body image appeared to boost the illusion; however, it was complex and tedious, affecting the practicability of IVBO, as individuals with MBID showed an extensive need for (control) habituation. Therefore, balancing IVBO immersion by focusing on habituation and lowering customization effort seems to be crucial to achieve both high SoE and usability. Owing to the limited attention span of people with MBID, tailoring to user and use appears to be important. Considering the cognitive limitations, we advise to avoid artificial interaction techniques that are implausible and

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increase the cognitive workload (eg, teleport) or evoke severe side effects, if possible, for the intended use context. In contrast, the use of artificial techniques comes at the expense of learning time and cognitive load, possibly interfering with other immersion parts. In conclusion, although designing IVR avatars for people with MBID is not fundamentally different, users' limitations challenge designers to develop tailored immersion procedures. Future studies should further investigate guidelines for IVR avatars in people with MBID by designing natural interactions, including multisensory integrations and other interaction approaches (eg, hand tracking and redirected walking). In addition, procedures and use cases for implicit and explicit learning should be explored, for instance, as a tool for playful health behavior change interventions. For this, the necessity of interactions should be reviewed carefully to avoid adverse effects (eg, cybersickness) and reduce the burden when interacting with IVR for people with MBID.

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Conflicts of Interest

None declared.

Multimedia Appendix 1
Semi-structured interview –IVR avatars for embodiment illusions in people with MBID.
[DOCX File , 16 KB - games_v10i4e39966_app1.docx]

Multimedia Appendix 2
Guidelines for designing IVR avatars for embodiment illusions in people with MBID.
[DOCX File , 17 KB - games_v10i4e39966_app2.docx]

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Abbreviations

FOV: field of view
HMD: head-mounted display
IK: inverse kinematics
IPQ: Igroup Presence Questionnaire
IVBO: illusions of virtual body ownership
IVE: immersive virtual environment
IVR: immersive virtual reality
MBID: mild to borderline intellectual disability
POV: point of view
SoE: sense of embodiment
SoP: sense of presence
UI: user interface
VEQ: Virtual Embodiment Questionnaire

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Original Paper

Impact of the Mobile Game FightHPV on Cervical Cancer Screening Attendance: Retrospective Cohort Study

Madleen Orumaa[1,2], PhD; Suzanne Campbell[1], MSc; Nathalie C Støer[1,3], PhD; Philip E Castle[4], PhD; Sagar Sen[5], PhD; Ameli Tropé[6], PhD; Adebola Adedimeji[7], PhD; Mari Nygård[1], PhD

[1]Department of Research, Cancer Registry of Norway, Oslo, Norway
[2]Department of Epidemiology and Biostatistics, Institute for Health Development, Tallinn, Estonia
[3]Norwegian Research Centre for Women's Health, Women's Clinic, Oslo University Hospital, Oslo, Norway
[4]Divisions of Cancer Prevention and Cancer Epidemiology and Genetics, National Cancer Institute, Rockville, MD, United States
[5]SINTEF, Oslo, Norway
[6]Section for Cervical Cancer Screening, Cancer Registry of Norway, Oslo, Norway
[7]Department of Epidemiology and Population Health, Albert Einstein College of Medicine, New York, NY, United States

Corresponding Author:
Mari Nygård, PhD
Department of Research
Cancer Registry of Norway
P.O. Box 5313 Majorstuen
Oslo, N-0304
Norway
Phone: 47 22928851
Email: mari.nygard@kreftregisteret.no

Abstract

Background: The wide availability of mobile phones has made it easy to disseminate health-related information and make it accessible. With gamification, mobile apps can nudge people to make informed health choices, including attending cervical cancer screening.

Objective: This matched retrospective cohort study examined the association between exposure to the FightHPV mobile app gamified educational content and having a cervical exam in the following year.

Methods: Women aged 20 to 69 years who signed an electronic consent form after downloading the FightHPV app in 2017 (intervention group) were matched 1:6 with women of the same age and with the same screening history (reference group) in 2015. To estimate the impact of exposure to the FightHPV app, we estimated cumulative incidence and hazard ratios (HRs) with 95% CIs. We used data from the Norwegian Cervical Cancer Screening Program database and Statistics Norway to determine screening participation and outcomes, respectively.

Results: We matched 3860 women in the control group to 658 women in the intervention group; 6 months after enrollment, 29.6% (195/658) of the women in the intervention group and 15.21% (587/3860) of those in the reference group underwent a cervical exam (P<.01). Women exposed to the FightHPV app were 2 times more likely to attend screening (adjusted HR 2.3, 95% CI 2.0-2.7), during which they were 13 times more likely to be diagnosed with high-grade abnormality (adjusted HR 12.7, 95% CI 5.0-32.5) than the women in the reference group.

Conclusions: Exposure to the FightHPV app significantly increased cervical cancer screening attendance across the various analyses and improved detection of women with high risk for cervical cancer. For the first time, we demonstrated the effectiveness of gamification combined with mobile technology in cancer prevention by empowering women to make active health-related decisions. Gamification can significantly improve the understanding of complicated scientific concepts behind interventions and increase the acceptance of proposed cancer control measures.

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KEYWORDS

mobile app; gamification; empowering; health literacy; cervical cancer screening; cancer prevention

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Introduction

Background

In 2019, the World Health Organization released the first evidence-based guideline on scaling up the use of digital interventions to reduce health inequities [1] and introduce a new era in health care [2]. Indeed, not only is successful dissemination of health-related information possible through the wide availability of mobile phones and social media, but these platforms also allow novel intervention designs for difficult-to-reach segments of the population, such as lower socioeconomical groups, youth, and older adults [3,4]. Theories suggest that health-related behavior is multidimensional and influenced by various factors, including information literacy [5-7]. Gamification is an innovative approach that motivates people to acquire new knowledge in a fun and engaging way [8], and it has proven to be a successful knowledge translation tool [9]. In eHealth, gamification has been widely used in various lifestyle mobile apps [9,10]; however, to our knowledge, its effectiveness has not yet been studied in a cancer prevention setting.

Cervical cancer screening aims to detect and treat cervical precancers, thereby reducing the cancer burden [11,12]. Screening is available in most high-income countries [13], where millions of women are invited to undergo free-of-charge or low-cost screening procedures every 3 to 5 years [11]. The most efficient, and often the most effective, cervical cancer screening is organized by public health programs, which promote equal access and ensure the quality of procedures related to screening exams and follow-up exams, diagnostic procedures for women with an abnormal screening exam result, and treatment of those with precancerous abnormalities or frank cancer.

Despite the general availability of cervical cancer screening in high-income settings, a subgroup of women is commonly observed not participating in these programs [14], leaving them at higher risk for the presence of precancerous abnormalities that may progress to cancer. A significant proportion, often >50%, of the cervical cancers diagnosed in these high-income settings are in unscreened and underscreened women [15]. Conversely, some women attend screening too frequently; that is, they attend at a shorter interval than is recommended. In a screening program context, frequent screening results in more harm, including detection and treatment of self-limiting conditions with a negative impact on women's mental and physical health, and increased health care costs [16,17]. Both under- and overscreening are related to the lack of understanding of health-related information [18].

Objectives

To improve the understanding of the importance of screening, we developed an innovative game-based mobile phone learning tool named FightHPV to educate its users about cervical cancer; its main causal agent, human papillomavirus (HPV); and its prevention. The FightHPV app has been documented to improve knowledge about screening, causes of cancer, and HPV [19]. A detailed description of the FightHPV app content, gameplay mechanics, and strategies used to engage the player can be found in Multimedia Appendix 1 (refer to Description of the FightHPV App [19-21]). However, it is still unclear whether exposure to the FightHPV app increases readiness to attend the cervical screening. To answer this question, we conducted a matched retrospective cohort study to examine the impact of being exposed to the FightHPV app gamified educational content and having a cervical exam in the following 12 months.

Methods

Overview

Our study took advantage of high-quality data from the Norwegian Cervical Cancer Screening Program (NCCSP) and Statistics Norway, both of which are nationwide registries with excellent completeness records with regard to collecting individual-level data over a long period of time. The study was restricted to Norway and to those who identified themselves through a nationally adapted, secure electronic BankID (a personal and simple electronic ID for secure identification used widely in Norway). The linkage between the study participants and the national registries ensured accurate information on outcomes and adjustment variables, such as education, employment status, income, and country of birth. These confounders have a documented effect on screening attendance in Norway [22] and might be associated with the use of health apps [23]. A more detailed description of the NCCSP and the linkage process is available in Multimedia Appendix 1 (refer to Description of the Norwegian Cervical Cancer Screening Program and the Linkage Process [24-27] and Figure S1).

Study Design

Electronic Consent and Enrollment of the Intervention Group

Every player who downloaded the app from the Apple App Store or Google Play Store and was residing in Norway had an opportunity to participate in the research project. In total, 896 players provided electronic consent by identifying themselves via BankID and were enrolled to the intervention group. The time at which a signature was provided through the electronic consent was defined as the start of the follow-up (T0i). The enrollment period was between March 1, 2017, and December 31, 2017. Among these 896 players, after excluding 238 (26.6%) for various reasons, we identified 658 (73.4%) women aged 20 to 69 years who were subsequently included in the study (Figures 1 and 2). By using individual screening data from the NCCSP, we categorized the intervention group by screening history at the enrollment date (T0i) into five mutually exclusive subgroups (Figure 2): (1) never screened, (2) only normal cytology results or negative HPV test, (3) abnormal cytology or positive HPV test but no histology ever, (4) at least one histology result, or (5) have ever received treatment for cervical abnormalities.

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Figure 1. Relevant time points for enrollment, screening history, and assessment periods for both intervention and reference groups.

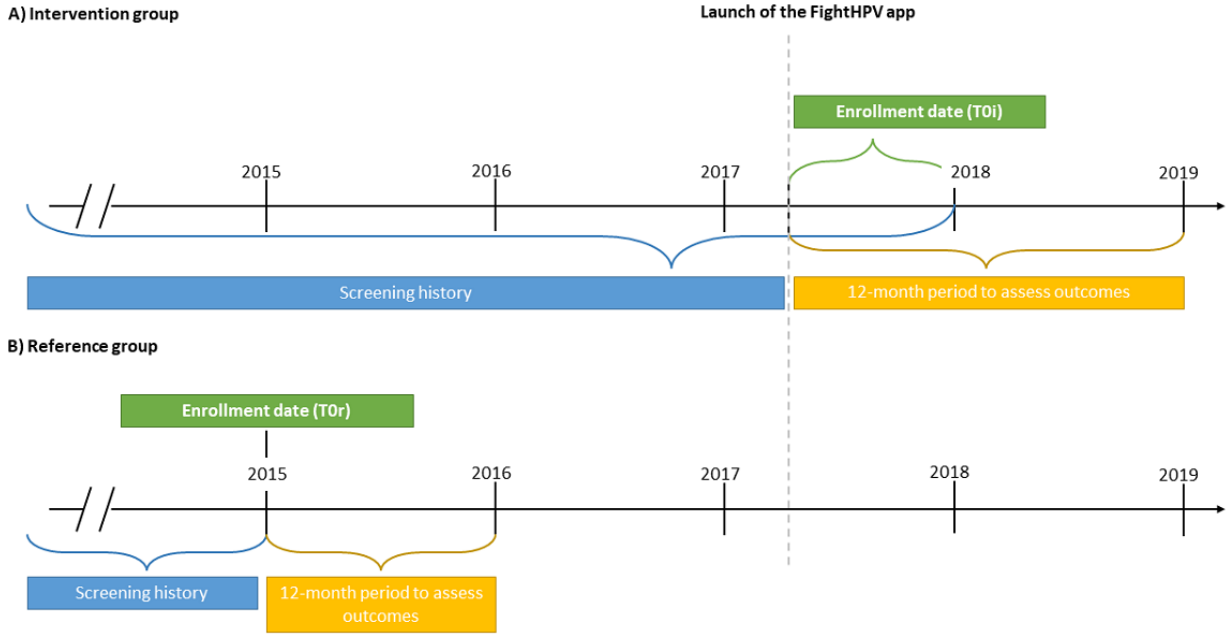
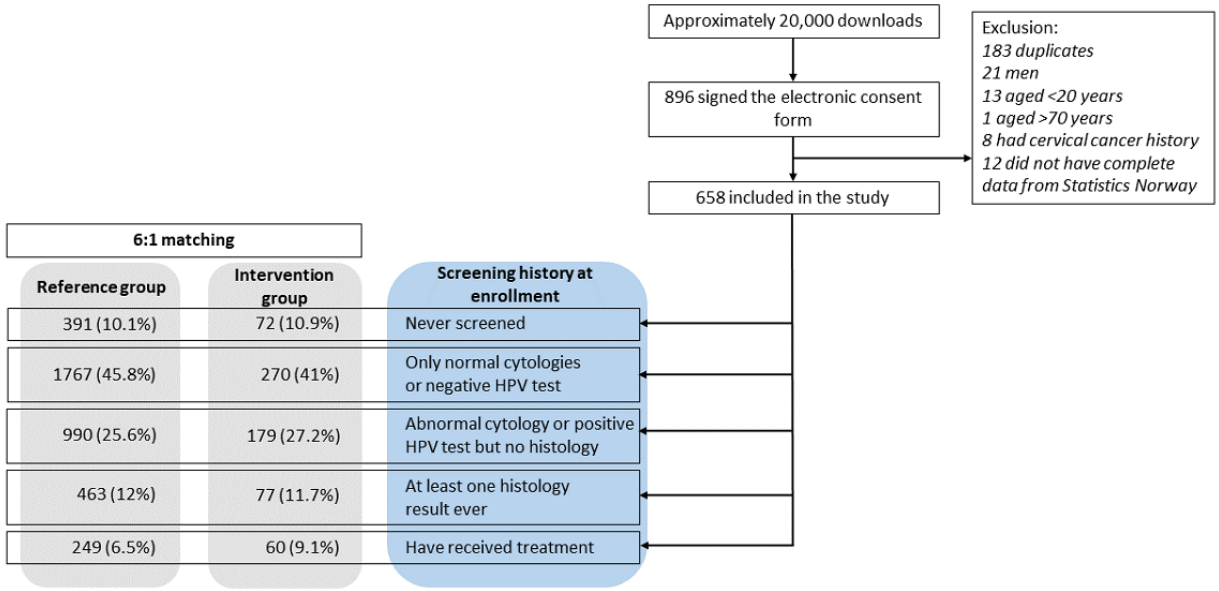


Figure 2. Selection of the intervention group and distribution of the screening history subgroups at enrollment for both the intervention (n=658) and reference (n=3860) groups. HPV: human papillomavirus.



Selection of the Reference Group

To avoid having been exposed to the FightHPV app launched in 2017, we defined January 1, 2015, as the enrollment date (T0r) for the reference group (Figure 1). Similar to the intervention group, we used NCCSP individual screening data and categorized all eligible women for the reference group into the previously described 5 mutually exclusive screening history subgroups on January 1, 2015 (enrollment date [T0r]). Women in the intervention group were matched 1:6 with women in the reference group by age at the enrollment date (T0) and screening history subgroup.

In total, 4818 participants were enrolled to the study and linked with Statistics Norway to obtain information on known confounders such as marital status, education, employment status, income, and country of birth. We used complete case analyses; therefore, participants with missing information regarding education (152/4818, 3.15%), country of birth (15/4818, 0.31%), employment status (46/4818, 0.95%), marital status (43/4818, 0.89%), or income (44/4818, 0.91%) were excluded. Thus, of the 4818 participants, after excluding 300 (6.23%), 658 (13.66%) were left in the intervention group and 3860 (80.12%) in the reference group for the analyses. After exclusions, the mean matching ratio was 1 case: 5.9 controls; 553 cases were matched 1:6, whereas 8 cases had <3 matches in the reference group (Figure 2).

Statistics

The impact of exposure to the FightHPV app on having a cervical exam and on the cervical exam outcome was assessed during the 1-year period after the enrollment date (T0i and T0r; Figure 1). We defined having a cervical exam as positive if at

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least one cervical exam result (cytology, HPV test, or histology) was registered during the 1-year period after the enrollment date. Cervical exam results were defined by test type and the results (cytology: normal vs abnormal, HPV test: negative vs positive, and histology: high-grade abnormality vs normal and low-grade abnormality) and compared between the intervention and reference groups.

The cumulative incidence of having a cervical exam was estimated as 1 minus the survival curve from the Kaplan-Meier estimator. Similarly, the 95% CI was estimated as 1 minus the upper and lower limits of the CI of the survival curve. Differences between the survival curves were tested with the logrank test.

Hazard ratios (HRs) with 95% CIs were estimated with Cox proportional hazard models. As the proportionality assumption was not fulfilled in most of the models based on Schoenfeld residuals, we fitted separate models for the 0- to 6-month and 7- to 12-month windows. Statistical models were adjusted for education (no education or mandatory education only, high school diploma, or higher education [more than high school diploma]), yearly income (<US $23,271, US $23,272-US $40,726, US $40,727-US $58,181, US $58,182-US $81,467, or ≥US $81,468), country of birth (Norway, other Nordic countries, or other), employment status (employed, self-employed, or unemployed or outside of the workforce), and marital status (single, married or registered partner, or divorced, separated, or widowed), in addition to the matching variables of age and screening history at enrollment. Associations between exposure to the FightHPV app and a positive HPV test, abnormal cytology, and histologically confirmed high-grade abnormality were also adjusted for expected screening activity during the 1-year period after T0.

To study adherence to national screening recommendations, we classified the observed screening activity after T0 into three categories: (1) not due for a screening test (to study whether FightHPV app use was associated with overscreening), (2) due for a follow-up exam (to identify how well women with an abnormal screening result fulfilled the follow-up recommendation), or (3) due for a screening test.

To assess the possible influence of age on responding to the FightHPV app content, we stratified the study participants into three groups based on their age at the enrollment date (T0): (1) below screening age (participants aged <24 years), (2) younger screening age (participants aged 24 to 39 years), or (3) older screening age (participants aged >39 years).

Ethics Approval

FightHPV is part of a project approved by the Norwegian Regional Ethics Committee (REK 2015/1926) and the institutional data protection officer. A liability and copyright terms and conditions of the game, along with logos from Oslo University Hospital and the Cancer Registry of Norway, have been incorporated into the app to enhance players' trust in the content.

Results

Study Population Characteristics

Matching variables of age and screening history at enrollment were similar for both groups (Table 1). At enrollment, 89.75% (4055/4518) of the participants had had at least one cervical exam recorded. Of these 4055 participants, 2056 (50.7%) had only normal cytology or a negative HPV result, and 1999 (49.3%) had at least one abnormal cytology or a positive HPV test, histology result, or treatment. Compared with the women in the reference group (n=3860), those in the intervention group (n=658) were more likely to be in the higher-education category, that is, more than high school diploma (393/658, 59.7%, vs 1997/3860, 51.74%; $P<.001$); born in Norway (612/658, 93%, vs 3235/3860, 83.81%; $P<.001$); and single (348/658, 52.9%, vs 1687/3860, 43.7%; $P<.001$); in addition, the women in the intervention group were also more likely to have higher income ($P=.002$).

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Table 1. Study population characteristics at enrollment by exposure status.

Variables	Intervention group (n=658)	Reference group (n=3860)	*P* value
Matching variables			
Age (years), median (IQR)	35 (28-45)	36 (28-45)	.63
Screening history at enrollment, n (%)			.13
Never screened	72 (10.9)	391 (10.1)	
Only normal cytology or negative HPV[a] test	289 (43.9)	1767 (45.8)	
Abnormal cytology or positive HPV test but no histology ever	160 (24.3)	990 (25.6)	
At least one histology result	77 (11.7)	463 (12)	
Treatment for cervical abnormalities ever	60 (9.1)	249 (6.5)	
Adjustment variables			
Education, n (%)			<.001
No education or mandatory education only	79 (12)	649 (16.8)	
Upper secondary	186 (28.3)	1214 (31.5)	
Higher education	393 (59.7)	1997 (51.7)	
Yearly income (US $), n (%)			.002
<23,271	87 (13.2)	410 (10.6)	
23,272 to 40,726	127 (19.3)	892 (23.1)	
40,727 to 58,181	189 (28.7)	1179 (30.5)	
58,182 to 81,467	166 (25.2)	1012 (26.2)	
≥81,468	89 (13.5)	367 (9.5)	
Country of birth, n (%)			<.001
Norway	612 (93)	3235 (83.8)	
Other Nordic countries	16 (2.4)	61 (1.6)	
Other	30 (4.6)	564 (14.6)	
Employment status, n (%)			.05
Employed	530 (80.5)	2952 (76.5)	
Self-employed	14 (2.1)	77 (2)	
Unemployed or outside of the workforce	114 (17.3)	831 (21.5)	
Marital status, n (%)			<.001
Single	348 (52.9)	1687 (43.7)	
Married or registered partner	229 (34.8)	1664 (43.1)	
Divorced or separated or widowed	81 (12.3)	509 (13.2)	

[a]HPV: human papillomavirus.

Impact of Exposure to the FightHPV App

During the year after enrollment, 44.2% (95% CI 40.3%-47.9%) of the participants in the intervention group and 27% (95% CI 25.6%-28.4%) of the participants in the reference group had a cervical exam (*P*<.01; Figure 3). The results from the adjusted Cox model supported this observation, showing that exposure to the FightHPV app was associated with a higher number of cytology or HPV tests after the 0- to 6-month and 7- to 12-month periods after enrollment (HR 2.2, 95% CI 1.8-2.5 and HR 1.5, 95% CI 1.2-1.9, respectively; Table 2). The women in the intervention group were more likely to return for a diagnostic test than those in the reference group in both time periods (0-6 months: HR 3.8, 95% CI 2.4-6.2; 7-12 months: HR 3.6, 95% CI 1.9-6.7; Table 2).

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Figure 3. Cumulative incidence of having a cervical exam 1 year after enrollment among the intervention and reference groups with 95% CIs.

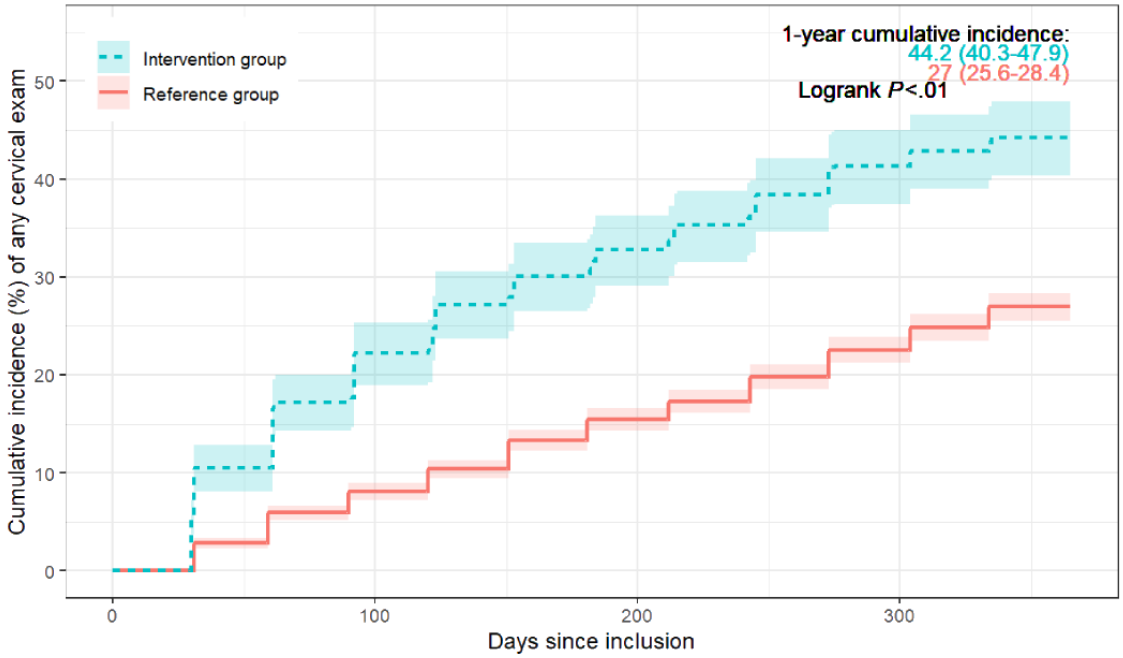

Table 2. Association between exposure to the FightHPV app and having a cytology or HPV test, diagnostic test (histology), or any cervical exam 1 year after the enrollment date (T0) stratified by time since the enrollment date (T0). A woman could have had both screening and diagnostic exams during the same period.

Test and time period (months)	Intervention group (n=658), n (%)	Reference group (n=3860), n (%)	Unadjusted HR[a] (95% CI)	Adjusted HR[b] (95% CI)
Cytology or HPV[c] test				
0 to 6	195 (29.6)	585 (15.2)	2.2 (1.8-2.6)	2.2 (1.8-2.5)
7 to 12	92 (19.9)	450 (13.7)	1.5 (1.2-1.9)	1.5 (1.2-1.9)
Diagnostic test (histology)				
0 to 6	29 (4.4)	45 (1.2)	3.8 (2.4-6.1)	3.8 (2.4-6.2)
7 to 12	16 (2.5)	31 (0.8)	3.2 (1.7-5.8)	3.6 (1.9-6.7)
Any cervical exam (cytology, HPV test, or histology)				
0 to 6	208 (31.6)	596 (15.4)	2.3 (2.0-2.7)	2.3 (2.0-2.7)
7 to 12	83 (18.4)	445 (13.6)	1.4 (1.1-1.8)	1.4 (1.1-1.8)

[a]HR: hazard ratio.

[b]Adjusted for education, country of birth, employment status, marital status, and income, in addition to the matching variables of screening history at enrollment and age.

[c]HPV: human papillomavirus.

Exposure to the FightHPV app was associated with a higher number of cervical exams, independent of expected screening activities as determined by the national screening guidelines. Among the women who were due for a screening test, 63.9% (95% CI 55.6%-70.7%) in the intervention group and 33.1% (95% CI 30.3%-35.7%) in the reference group had a cervical exam 1 year after enrollment (*P*<.01; Figure 4). Exposure to the FightHPV app resulted in increased cervical exams during the first 6 months after enrollment (HR 3.3, 95% CI 2.6-4.3) but not during the 7- to 12-month period after enrollment (Table 3). Among the women who needed a follow-up exam, 67.5% (95% CI 55.7%-76.1%) in the intervention group and 57% (95% CI 50.9%-62.4%) in the reference group had a cervical exam during the 1-year period (*P*=.02; Figure 4). Exposure to the FightHPV app resulted in increased cervical exams during the first 6-month period after enrollment (HR 1.8, 95% CI 1.2-2.6) but not during the 7- to 12-month period after enrollment (Table 3). Among the women who were not due for a screening test, 32.1% (95% CI 27.5%-36.5%) in the intervention group and 20.6% (95% CI 19.5%-22.2%) in the reference group had a cervical exam in the 1-year period (*P*<.01; Figure 4), and exposure to the FightHPV app was associated with a higher number of cervical exams during both time periods (0-6 months: HR 1.9, 95% CI 1.5-2.5; 7-12 months: HR 1.5, 95% CI 1.1-2.0; Table 3).

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Figure 4. Cumulative incidence of having a cervical exam 1 year after enrollment among the intervention and reference groups with 95% CIs across expected screening activity subgroups and study participants' age.

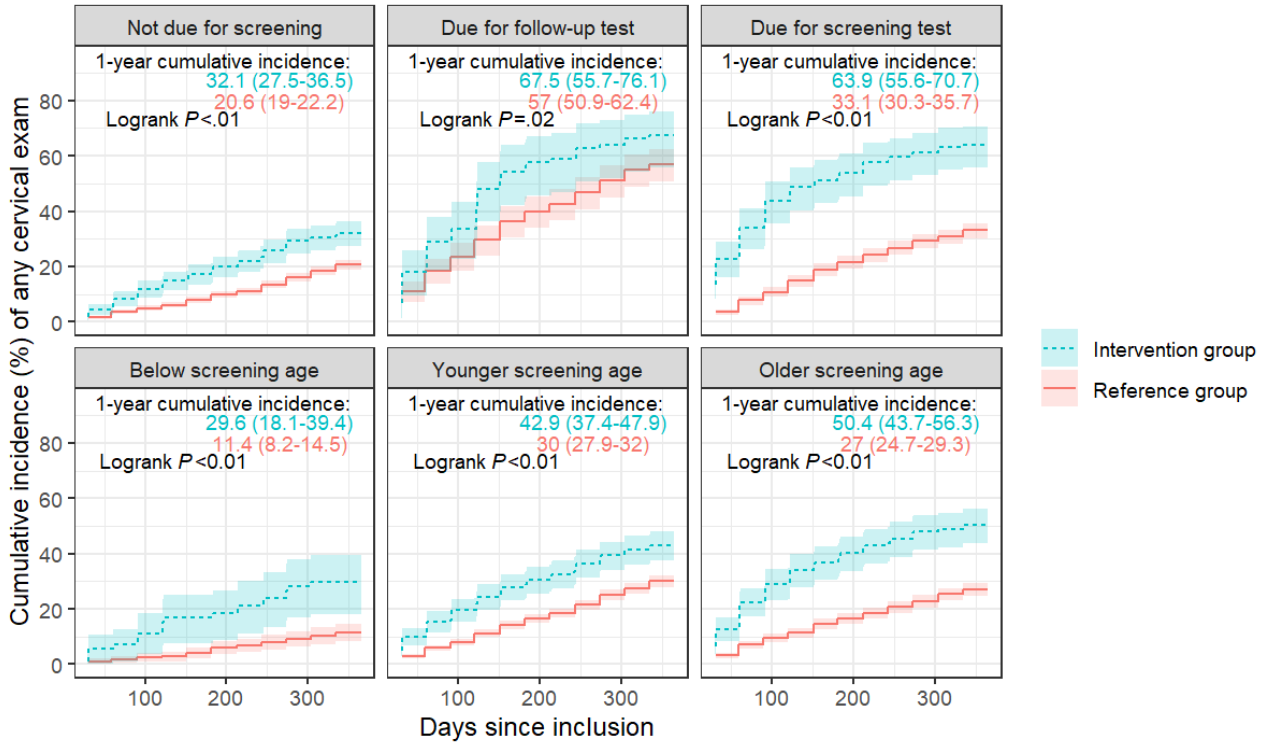

Table 3. Association between exposure to the FightHPV app and having a cervical exam during the 1-year period after the enrollment date (T0) across expected screening activity subgroups, reflecting adherence to national screening recommendations, stratified by time since the enrollment date (T0).

	Any cervical exam (cytology, HPV[a] test, or histology)	
	0 to 6 months	7 to 12 months
Not due for screening test (n=2856)[b]		
Intervention group (n=416), n (%)	76 (18.3)	58 (17.1)
Reference group (n=2440), n (%)	239 (9.8)	264 (12)
Adjusted HR[c,d] (95% CI)	1.9 (1.5-2.5)	1.5 (1.1-2.0)
Due for follow-up exam (n=367)[e]		
Intervention group (n=83), n (%)	47 (56.6)	9 (25)
Reference group (n=284), n (%)	113 (39.8)	49 (28.7)
Adjusted HR (95% CI)	1.8 (1.2-2.6)	1.1 (0.5-2.3)
Due for screening test (n=1295)[f]		
Intervention group (n=159), n (%)	85 (53.8)	16 (21.9)
Reference group (n=1136), n (%)	244 (21.5)	132 (14.8)
Adjusted HR (95% CI)	3.3 (2.6-4.3)	1.6 (0.9-2.7)

[a]HPV: human papillomavirus.

[b]Not due for screening test: women aged <25 years; last cervical exam was <2.8 years before the enrollment date (T0); only normal test results during the last 3 years.

[c]HR: hazard ratio.

[d]Adjusted for education, country of birth, employment status, marital status, and income, in addition to the matching variables of screening history at enrollment and age.

[e]Due for follow-up exam: women at any age; had an abnormal primary cervical screening exam 3 years before the enrollment date (T0).

[f]Due for screening test: women aged >25 years; no cervical exam results <2.8 years before the enrollment date (T0).

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The 1-year cumulative incidence of a cervical exam was significantly higher among those exposed to the FightHPV app, regardless of age. The proportion of women who had a cervical exam in the intervention group versus those in the reference group was 50.4% (95% CI 43.7%-56.3%) versus 27% (95% CI 24.7%-29.3%) in the older screening age group (*P*<.01), 42.9% (95% CI 37.4%-47.9%) versus 30% (95% CI 27.9%-32%) in the younger screening age group (*P*<.01), and 29.6% (95% CI 18.1%-39.4%) versus 11.4% (95% CI 8.2%-14.5%) among those below the screening age (*P*<.01), respectively (Figure 4). This difference was more pronounced during the first 6-month period after enrollment, being almost 3 times higher among those exposed to the FightHPV app in the older screening age group (HR 2.7, 95% CI 2.1-3.5), twice as high in the younger screening age group (HR 1.9, 95% CI 1.5-2.4), and 5 times higher among those below the screening age (HR 5.3, 95% CI 2.5-11.3; Table 4). In the 7- to 12-month period after enrollment, the magnitude of association for each age group was lower and only borderline significant for those below the screening age and the older screening age group (Table 4).

Comparing cervical exam outcomes, the women in the intervention group were 4 times more likely to test positive for HPV (HR 4.1, 95% CI 2.2-7.8), twice as likely to have abnormal cytology (HR 2.2, 95% CI 1.3-3.7), and 12 times more likely to be diagnosed with a high-grade abnormality (HR 12.7, 95% CI 5.0-32.5) compared with the women in the reference group during the first 6 months after enrollment (Table 5). During the 7- to 12-month period after enrollment, the women in the intervention group were 2 to 3 times more likely to test positive for HPV (HR 2.3, 95% CI 1.2-4.4), have abnormal cytology (HR 2.8, 95% CI 1.5-5.2), and be diagnosed with a high-grade abnormality (HR 3.0, 95% CI 1.0-9.0) compared with the women in the reference group (Table 5).

In addition, separate analyses on education, screening history, country of birth, and income were conducted (Multimedia Appendix 1), all of which confirmed a strong and consistent association between exposure to the FightHPV app and having a cervical exam within a year.

Table 4. Association between exposure to the FightHPV app and having a cervical exam during the 1-year period after the enrollment date (T0) across the study participants' age and stratified by time since the enrollment date (T0).

	Any cervical exam (cytology, HPV[a] test, or histology)	
	0 to 6 months	7 to 12 months
Below screening age (n=465)[b]		
Intervention group (n=70), n (%)	13 (18.3)	8 (13.8)
Reference group (n=395), n (%)	24 (6.1)	21 (5.7)
Adjusted HR[c,d] (95% CI)	5.3 (2.5-11.3)	2.4 (1.0-5.6)
Younger screening age (n=2351)[e]		
Intervention group (n=344), n (%)	99 (28.9)	48 (19.7)
Reference group (n=2007), n (%)	331 (16.5)	271 (16.2)
Adjusted HR (95% CI)	1.9 (1.5-2.4)	1.2 (0.9-1.7)
Older screening age (n=1702)[f]		
Intervention group (n=244), n (%)	96 (39.3)	27 (18.2)
Reference group (n=1458), n (%)	241 (16.5)	153 (12.6)
Adjusted HR (95% CI)	2.7 (2.1-3.5)	1.5 (1.0-2.3)

[a]HPV: human papillomavirus.

[b]Below screening age: women aged <24 years.

[c]HR: hazard ratio.

[d]Adjusted for education, country of birth, employment status, marital status, and income, in addition to the matching variables of screening history at enrollment and age.

[e]Younger screening age: women aged between 24 and 39 years.

[f]Older screening age: women aged >39 years.

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Table 5. Association between exposure to the FightHPV app and having a positive human papillomavirus (HPV) test result, abnormal cytology, or high-grade abnormality diagnosis 1 year after the enrollment date (T0) stratified by time since the enrollment date (T0).

Test result and time period (months)	Intervention group (n=658), n (%)	Reference group (n=3860), n (%)	Unadjusted HR[a] (95% CI)	Adjusted HR[b] (95% CI)
Positive HPV test				
0 to 6	20 (3)	23 (0.6)	5.2 (2.8-9.4)	4.1 (2.2-7.8)
7 to 12	15 (2.4)	31 (0.8)	2.9 (1.6-5.4)	2.3 (1.2-4.4)
Abnormal cytology				
0 to 6	24 (3.6)	48 (1.2)	3.0 (1.8-4.8)	2.2 (1.3-3.7)
7 to 12	16 (2.5)	33 (0.9)	2.9 (1.6-5.3)	2.8 (1.5-5.2)
High-grade abnormality				
0 to 6	16 (2.4)	6 (0.2)	15.8 (6.2-40.5)	12.7 (5.0-32.5)
7 to 12	5 (0.8)	12 (0.3)	2.5 (0.9-7.1)	3.0 (1.0-9.0)

[a]HR: hazard ratio.

[b]Adjusted for education, country of birth, employment status, marital status, income and expected screening activity, in addition to the matching variables of screening history at enrollment and age.

Discussion

Principal Findings

To our knowledge, the FightHPV app is the first-ever game-based health-related–information intervention tool developed to increase demand for cancer screening among the screening program target population. The FightHPV app gamified scientifically accepted principles of cervical cancer prevention to augment the processing and contextualizing of health information, with the ultimate goal to nudge the player to attend screening. We demonstrated that women who used the FightHPV app were up to 3 times more likely to make an appointment and have a cervical exam than women who were not exposed to the app and its educational content, regardless of previous screening history or age.

Exposure to the FightHPV app had the highest impact on women during the first 6 months after exposure but continued to influence health-seeking behaviors, albeit to a lesser effect, during the 7- to 12-month period. This pattern was consistent across all expected screening activity and age categories. The desire to seek possibilities to have a cervical exam as soon as possible may reflect the unease regarding forgetting to book an appointment and, consequently, missing any potential cervical abnormalities that might need intervention. Studies have shown that exposure to information motivates positive health-seeking behaviors [7,28], highlighting the critical role of health literacy, in which awareness or knowledge of a health condition and its consequences can elicit certain behaviors among those affected by the condition. Health literacy is a concept emerging from social cognitive and social efficacy theories, which explain how perception and interpretation of health information influence behavior. Systematic reviews [29,30] and other studies [31] have highlighted that increased health literacy affects reproductive health behaviors and outcomes among women, especially those at risk for cancer.

We detected that the FightHPV app players had almost 13 times higher risk of being diagnosed with a histologically confirmed precancerous abnormality than the women in the reference group, whereas, in comparison, the overall attendance was improved approximately 3 times. This striking difference in participation in screening and the risk of those participating after exposure to the FightHPV app indicate that the game-based intervention influenced how users understood and interpreted the relevance and value of the screening test [32,33]. This is well in line with what we learned from focus group discussions during the development of the FightHPV app [19], where it was documented that the FightHPV app encouraged players to think about their behavior and reflect on the personal risks of cervical cancer. The observed higher rates of precancerous abnormalities in the intervention group suggests that those who perceived themselves to be at higher risk also attended the screening. This suggests that the FightHPV app not only increased awareness about the risks associated with cervical cancer but also helped to overcome emotional and practical barriers to attend the screening [22,32].

It is important to highlight that the reference and intervention cohorts were similar with regard to age and screening history—the latter is one of the strongest modifiers of cervical cancer risk. Furthermore, screening attendance is also used as a proxy to describe health consciousness and health behavior. Access to complete and accurate information on screening exams and the results for each participant allowed matching based on screening history at enrollment, which, in turn, ensured that both groups were comparable with respect to those never screened, those who had previously normal or abnormal exams, and those who had an invasive histology exam. Therefore, we argue that the observed differences cannot be explained by differences in cervical cancer risk and are rather a result of increased awareness from using the FightHPV app.

We also considered the possibility that the reported increase in the incidence of precancerous abnormalities over the last decades [34] might explain the higher rate of detection of high-grade abnormalities in the intervention group participants, who were enrolled in 2017, some 2 years after the reference

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group enrollment (2015). However, it is highly unlikely that birth cohorts 2 years apart represent differences in behavior of this magnitude. In addition, HPV-based screening with more aggressive clinical management algorithms had already been introduced in Norway in 2015 and therefore had a similar impact on the intervention and reference groups [35].

We have used cervical cancer screening as an example of a possible application field where knowledge translation via gamification and mobile phones can be used. In cervical cancer screening, women's attitude toward screening, along with organizational factors, is crucial [36]. It has been found that the decision to skip the screening is usually not an active choice but rather a lack of knowledge or willingness to act [37]; hence, these interventions promoting these aspects should be targeted. Our results are in line with evidence that suggests that theory-based and culturally and linguistically sensitive educational interventions conducted by health advisors positively affect screening rates [18].

The application of game mechanics in this nongame context injected a little fun into health communications, as previously described [9,19]. In-game immediate feedback, in terms of cumulative scores and visible and auditable incentives after solving a puzzle or failing to do so, contributed to the game flow and allowed players to reach a state of absorption, which is believed to be an important aspect in the development of consciousness and enjoyment [4]. Solving puzzles provides an immediate feeling of achievement, and the player will gravitate toward more difficult puzzles. The great advantage of failing to solve a puzzle is that the player has an opportunity to repeat the puzzle and challenge. Short in-game messages in the FightHPV app provided narratives for each episode and at the end of each puzzle to increase contextualization of the information for the players.

The World Health Organization guideline (refer to the Introduction section) highlights the importance of taking advantage of digital technology interventions to contribute to health system improvements [1]. Among the 9 key recommendations, 1 is dedicated to targeted client communication for behavior change. According to the guideline, the transmission of health information via mobile phones is effective, acceptable, and uses fewer resources than nondigital interventions. This study adds to the growing body of evidence indicating that health-related information can be effectively distributed via mobile phones; however, it must be emphasized that interventions such as the FightHPV app will not serve the final goal of increasing cervical cancer screening attendance and hence reducing cervical cancer incidence and mortality without an existing and working screening program. In resource-constrained settings where access to screening is often nonexistent, the focus should first be on building up the screening program and improving health policy in general.

Our experience of developing the FightHPV app suggests that a successful team to customize the app would require a group of public health specialists, a graphic designer, and 1 or 2 mobile app developers. Together with a sociologist, the public health specialists can create the country- and language-specific content for in-game text messages, assess the game characters' appropriateness, and, if needed, guide the graphic designer to make the adjustments. Once the content is confirmed, developers with Android and Swift programming experience can make the necessary modifications, and game testers in the target group can confirm app readiness. After the launch, a marketing strategy is required to get people interested in the app and ensure sustainable app uptake. Our experience showed that after a promotional video was published on the NCCSP Facebook page, there was a rapid increase in downloads, which subsided after a week (Figure S2 in Multimedia Appendix 1). The regular promotion of the app is crucial for a long-term effect on screening attendance.

Strengths and Limitations

Our study was designed to leverage Norwegian high-quality registry-based data. Accurate information about outcomes and controlling variables obtained from the screening registry and Statistics Norway resulted in increased internal validity of the study. Although only 658 women living in Norway were enrolled to the intervention group, we believe this figure represents a subpopulation of women who are willing to change their screening behavior. We demonstrated that the intervention had a significant positive effect on the future screening–related decisions of this part of the population. We argue that this is the most crucial part of the population to reach because those unwilling to change their health behavior will not benefit from using this app. However, more studies are needed to replicate the observed effect of gamification on cancer screening in different health care settings and populations.

Despite the high number of total worldwide downloads, we only enrolled Norwegian citizens because it was crucial to obtain personal-level data from the Norwegian health registries, and it made the comparison of outcomes between the intervention and reference groups meaningful because both groups had to adhere to the same national cervical cancer screening guidelines (such as a 3-year screening interval and the starting age of screening), which typically differ across countries.

Because of the data protection law, we were not allowed to follow the participants' progress in the game or played time. Therefore, we were not able to assess how the exposure time might have influenced future screening–related decisions. However, we assume that most of the people who confirmed their willingness to participate spent a reasonable time exploring the app and therefore were exposed to its educational content. Although we lacked data on censoring, such as emigration and death data, during the 1-year period after enrollment for the intervention group, we assume that this was indifferent and low among both the intervention and reference groups. If anything, the associations between exposure to the FightHPV app and screening participation might be somewhat underestimated, although sensitivity analyses indicated a minimal effect only.

Conclusions

Exposure to the FightHPV app was significantly associated with the increased number of cervical exams across the various analyses. For the first time, we demonstrated the effectiveness of gamification combined with mobile technology in cancer prevention by empowering women to make an active

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health-related decision to attend cervical cancer screening. Gamification can significantly improve the understanding of complicated scientific concepts behind suggested interventions and increase the acceptance of proposed cancer control measures.

Acknowledgments

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Authors' Contributions

MN and PC designed the study and, together with MO, SC, and NCS, developed the methods, interpreted the analyses, and contributed to the writing of this paper. MO created the first draft of the manuscript. PEC, AA, AT, and SS assisted with the interpretation of the findings and contributed to the writing of this paper. All authors provided intellectual contributions to the manuscript reviews and approved the final version for submission. MO, MN, SC, and NCS verified the data.

Conflicts of Interest

MN has received research grants from Merck & Co, Inc, through the affiliating institute.

Multimedia Appendix 1
Additional information on study methods and results.
[DOCX File , 585 KB - games_v10i4e36197_app1.docx]

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Abbreviations

HPV: human papillomavirus
HR: hazard ratio
NCCSP: Norwegian Cervical Cancer Screening Program

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Original Paper

A Web-Based Gaming Approach to Decrease HIV-Related Stigma: Game Development and Mixed Methods Evaluation

Xiaoxiao Zhang[1], BA, MA, PhD; Erman Lai[1], BA, MA

School of Journalism and Communication, Jinan University, Guangzhou, China

Corresponding Author:
Xiaoxiao Zhang, BA, MA, PhD
School of Journalism and Communication
Jinan University
601 West Huangpu Ave
Tianhe District
Guangzhou, 510632
China
Phone: 86 13798184756
Email: xiaoxiaozhang@jnu.edu.cn

Abstract

Background: The stigma faced by people living with HIV causes difficulties in the treatment of HIV/AIDS. Decreasing this stigma is thus no less urgent than implementing behavioral interventions. Serious games are being increasingly adopted as an intervention mechanism to control HIV/AIDS around the world. However, the development and evaluation of these games in China are far from adequate.

Objective: This research aimed to help decrease HIV-related stigma in China via the development and evaluation of a serious game, as well as promote a participatory gamification culture for health interventions.

Methods: Initially, a serious game was developed using free resources from a user-generated content website. Then, quantitative and qualitative methods were employed for game evaluation. A randomized controlled trial was conducted to explore the game's effect on HIV-related stigma. The trial included 167 university students, who were randomly allocated to game and control groups. After the experimental evaluation, focus group discussions were held with 64 participants, who were invited to form 16 groups.

Results: The game was called The Second Kind of Life with HIV (SKLWH), which is a free online game that can be played on computers and smartphones. This game hopes to publicize that people living with HIV can live a normal life, that is, a second life different from that imagined by the public. Based on the gamification practice of SKLWH, the participatory serious game development model (PSGDM) was proposed, which guided the development of 3 other HIV-themed games. The trial showed that intimacy stigma was much more severe than morality stigma and personal interaction stigma. Females were more tolerant of morality stigma than males (mean score: 1.29 vs 1.50; P=.01). The game intervention showed an advantage in decreasing intimacy stigma (mean score [game vs control]: 2.43 vs 2.73; P=.04). The group discussions validated the quantitative results and provided further in-depth information. The game intervention was largely preferred by participants, and the belief in intimacy impossibility was commonly expressed by participants when considering their relationship with people living with HIV.

Conclusions: HIV/AIDS education should adopt appropriate media interventions to mitigate different dimensions of HIV-related stigma. Serious games should be used to decrease intimacy stigma, which is the hardest form to diminish. It is expected that the PSGDM can promote the development of more health games. Furthermore, HIV/AIDS intervention requires interdisciplinary efforts and cooperation that will allow more people to participate and share the responsibility of promoting health.

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KEYWORDS

serious games; interactive narrative games; games for health; entertainment education; digital health intervention; game development and evaluation; mixed methods evaluation; participatory culture; people living with HIV; HIV-related stigma; intimacy stigma

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Introduction

Background

Despite progress in HIV/AIDS prevention and control, its prevalence in China has not declined [1]. In 2020, the death toll of AIDS in the country was 4 times that of COVID-19 [2]. In the past 3 years, it has always ranked first among class-A and class-B infectious diseases [2,3]. People living with HIV in China are, to a large extent, ostracized by the public as "others." This stigma causes difficulties in the prevention and treatment of the disease. Decreasing this stigma is thus no less urgent than implementing behavioral interventions.

In HIV/AIDS education for young people, digital games are an intervention strategy with great potential [4]. These games are increasingly adopted in the international academic context [5-8]. In China, HIV/AIDS educational games are in their infancy. Besides the games developed by the team of the author XZ, there is only a short list of serious games that focus on HIV/AIDS, including Winter AIDS: a Wondrous Journey, Crossroad in Life Path, Waterloo Bridge Café, and AIDS Fighter · Health Defense. Furthermore, HIV/AIDS-themed games, both in China and abroad, usually focus on knowledge education, behavioral change, and antiretroviral treatment uptake. Very few games focus on decreasing HIV-related stigma. As an interdisciplinary attempt, this research is among the first in China to use a web-based gaming approach to mitigate stigma and help diminish the prevalence of HIV/AIDS.

In this research, a serious game called The Second Kind of Life with HIV (SKLWH) [9] was created for the HIV/AIDS education of students. Through role-playing in simulated life scenarios, the game allows players to experience the discrimination faced by people living with HIV. Quantitative and qualitative methods, that is, a randomized controlled trial and focus groups, respectively, were applied to evaluate the educational game. This research proposes the participatory serious game development model (PSGDM) and integrates game development and effect evaluation. By doing so, it aims to make up for the current paucity of studies on independent games, health function games, and other serious games in Chinese academia [10,11]. In particular, this research wishes to address the lack of effect evaluations of HIV/AIDS educational games based on randomized controlled trials [12].

HIV-Related Stigma

Stigma refers to labeled differences. It is the result of social construction. As Link and Phelan have noted, everyone is different, but when certain differences are associated with negative ideas, they separate "us" from "them," resulting in the loss of social status and discrimination for the individuals who are negatively labeled [13]. Stigma is widespread in social life. It is an ancient dilemma for humanity, involving race, ethnicity, gender, religion, health, and many other factors. HIV-related stigma belongs to the realm of health. Its wide prevalence and social consequences are considered "the third phase of the HIV pandemic" [14].

HIV-related stigma is one of the major obstacles to the prevention and control of HIV/AIDS. This problem is usually discussed from different sides to reflect the discrimination that people living with HIV encounter in various aspects of life, such as society's moral condemnation of people living with HIV [15,16], the stigma they experience in their personal interactions [15-17], and the prejudices against intimate relationships with them [18-21]. Accordingly, this research discusses HIV-related stigma at the level of morality, personal interaction, and intimacy. Based on the logic of the social distance scale [22], marriage intention best reflects people's acceptance of a certain group, while marriage resistance is the hardest to overcome. Moreover, empirical studies have shown that among the items that measure HIV-related stigma, the most frequently chosen one is refusing to have a date with a person living with HIV [20]. Therefore, we formulated the following 2 research hypotheses: (1) HIV-related intimacy stigma is greater than HIV-related morality stigma (hypothesis 1); and (2) HIV-related intimacy stigma is greater than HIV-related personal interaction stigma (hypothesis 2).

Effects of Serious Games on HIV-Related Stigma

Sontag has argued that AIDS metaphors that generate fear and inflict stigma must be exposed, criticized, belabored, and used up [23], and this cannot be done without media communication. Since the early 1990s, the mass media have engaged in HIV/AIDS prevention and control, and they are now regarded as an effective "vaccine" against HIV infection. Among various media forms, serious games advocate the idea of entertainment education, expose social injustice, and reflect on discrimination; they are thus an effective intervention for communicating prosocial information [24]. HIV/AIDS educational games can be classified into many types, including racing games (eg, Fast Car: Travelling Safely Around the World), board games (eg, Make a Positive Start Today!), card games (eg, Mieux connaître les IST/VIH/SIDA), hero combat games (eg, AIDS Fighter · Health Defense), and narrative games (eg, Tumaini). SKLWH, the trial material used in this research, is an interactive narrative game.

Based on the entertainment overcoming resistance model (EORM), entertainment education media can overcome resistance from the audience by way of narratives, thus having a more positive effect on persuasion compared to traditional educational methods [25,26]. Digital games enable learning from interactive experience, which no other interventions can match [27]; they can also change attitude and behavior in an engaging environment [24]. The entertainment education strategy of serious games can make HIV/AIDS-related experiences more perceptible and familiar to players. They can thus mitigate discrimination through players' identification with people living with HIV. Overall, it is predicted that games have a more significant effect on decreasing HIV-related stigma. The following 3 hypotheses were thus proposed: (1) After the intervention, the game groups are more tolerant than the control groups in terms of morality stigma (hypothesis 3); (2) After the intervention, the game groups are more tolerant than the control groups in terms of personal interaction stigma (hypothesis 4); and (3) After the intervention, the game groups are more tolerant than the control groups in terms of intimacy stigma (hypothesis 5).

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A great number of issues related to sex exhibit gender differences. HIV/AIDS interventions do not have the same effect on different genders [28]. Existing studies indicate that females show less discrimination against people living with HIV than males [18,29,30]. However, one study suggested that females are more tolerant of people living with HIV than males in terms of morality stigma and personal interaction stigma, but that there is no significant gender difference regarding intimate interaction stigma [21]. Given this evidence, we formulated the following 2 hypotheses: (1) Females are more tolerant of people living with HIV than males in terms of morality stigma (hypothesis 6); and (2) Females are more tolerant of people living with HIV than males in terms of personal interaction stigma (hypothesis 7).

Methods

Method 1: Game Development

Based on the EORM, SKLWH was designed between August 2018 and April 2019 by 5 master's students using free resources of Cheng Guang, a popular user-generated content game website in China, under the supervision of the author XZ. The game is freely accessible from computers and smartphones. Digital technology means for HIV/AIDS education represent both an intervention delivery tool and a research tool [31]. Through gamification, social experiments can be conducted [32]. From this perspective, games can be seen as an "alternative laboratory" that helps break limited mindsets [33]. As a research method, serious gamification aims to convert the idea of entertainment education into practice, which involves constructing external and internal game grammar. According to Sun [34], external game grammar is related to specific social practices and identities, while internal game grammar is related to narrative elements in the form of games. The game development of this study involved designing and combining the external and internal grammar of SKLWH, and then, the game's effect was evaluated with a randomized controlled trial and focus group discussions.

Method 2: Experimental Evaluation

Research Procedure

The researchers invited university students to fill in a recruitment questionnaire through WeChat, China's largest social media platform. A total of 167 students from 7 universities in Guangzhou were recruited to voluntarily participate in the offline experiment from May 25 to June 2, 2019, and on March 21, 2021. The participants were aged between 17 and 28 years, with an average age of 20 years. They were allocated to the game and control groups using random numbers. A total of 27 participants were excluded during the data cleaning process (25 had already accessed the material and 2 provided careless responses). Data from the remaining 140 participants were obtained and deemed effective, as the sample size was larger than the minimal requirement of 128 (α=.05, power=0.8, effect size=0.25), which was calculated with G*Power (University of Dusseldorf). Finally, the trial had the following 4 groups: female game group (36 participants), male game group (36 participants), female control group (34 participants), and male control group (34 participants).

The game SKLWH served as the media intervention for the treatment groups. Its main content was converted into pictures and text, and sent to the control groups through WeChat posts. Both the game groups and control groups used smartphones to access their materials, thus ensuring consistency of presentation. The students did not know what kind of materials they would be exposed to before the trial. Each participant either played the game or read the WeChat posts, and immediately afterward, they filled out a questionnaire. There was no trial registration for this study, because when the authors started recruitment in April 2019, their university did not have such a requirement or tradition for social science disciplines. Moreover, when the authors started recruitment, their university did not have an ethical committee for the social sciences. As with a previous study [35], ethical rules were observed as much as possible in the course of this research. Each subject participated after providing informed consent, and was informed of privacy protection and the right to withdraw from the trial at any time.

Measures

The dependent variable of this research was HIV-related stigma, which involves 3 dimensions: morality stigma, personal interaction stigma, and intimacy stigma. The short HIV stigma scale was used to assess HIV-related stigma. This scale has 12 items, and each item uses a 4-point Likert scale (1, "strongly disagree" to 4, "strongly agree"). Some items were recoded, with higher scores indicating higher degrees of stigma. Missing values were replaced with means. This research reduced the scale's dimensionality via principal component analysis. The Kaiser-Meyer-Olkin value of the factor analysis was 0.82, and the Bartlett test of sphericity was significant (P<.001). Three dimensions were identified after deleting 2 items, which cumulatively explained 72.68% of the variance. The first dimension was personal interaction stigma (Cronbach α=.86), and a sample statement for this was "People living with HIV should be allowed to study with others." The second dimension was intimacy stigma (Cronbach α=.90), and a sample statement for this was "I'm not willing to marry a person living with HIV." The third dimension was morality stigma (Cronbach α=.64), and a sample statement for this was "Only those infected by HIV via blood transfusions or injections in hospitals deserve care and treatment."

Method 3: Focus Group Discussions

Immediately after the experimental evaluation, the researchers conducted group discussions to obtain feedback on SKLWH and HIV-related stigma. Sixty-four trial participants were invited to form 16 groups for discussion (Table 1) before the data reached saturation and new information could not be found. Participants in groups 1 to 9 played the game, while those in groups 10 to 16 read the WeChat posts. With the consent of the participants, the discussions were recorded and transcribed for further analysis.

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Table 1. Composition of the focus groups.

Group	Number of participants	Gender of participants
Group 1	3	One male and two females
Group 2	5	Five females
Group 3	2	One male and one female
Group 4	6	One male and five females
Group 5	2	One male and one female
Group 6	5	Two males and three females
Group 7	3	Three males
Group 8	2	Two males
Group 9	2	Two males
Group 10	5	Two males and three females
Group 11	6	Three males and three females
Group 12	6	Two males and four females
Group 13	2	One male and one female
Group 14	6	Four males and two females
Group 15	5	One male and four females
Group 16	4	Four males

The discussion centered on the following questions: Which is your favorite channel to receive HIV/AIDS education—games, WeChat, or lectures? Why do you prefer this channel? In your opinion, what kinds of situations are people living with HIV facing in society?

Participants in groups 1 to 9 who played SKLWH were also asked the following questions: Is SKLWH attractive to you? If so, why? In your opinion, is SKLWH effective for HIV/AIDS education? Did you identify with Qin Qin, the protagonist of SKLWH, when playing the game? How can SKLWH be improved?

Results

Game Development Results

External Grammar of SKLWH

The experience of serious game playing is a process of value-based learning [36]. As SKLWH is a serious game reflecting on HIV-related stigma, the values constructed in its text are of great importance. After collecting extensive original stories and consulting experts in HIV/AIDS education, the design team decided that the game would reflect the stigma faced by people living with HIV from the perspective of morality, personal interaction, and intimacy, with an emphasis on the idea that people's right to marry and have romantic relationships should not be hampered by disease. The main character of the game is Qin Qin, a female college student who has HIV. By taking the role of Qin Qin, players can experience the life of people living with HIV. In SKLWH, a character not living with HIV called Jiang Zheyu likes Qin Qin and confesses his affection for her. Qin Qin then reveals her HIV status, but Jiang Zheyu does not give up his feelings for her (Figure 1). Qin Qin (ie, the player) finally decides whether to marry Jiang Zheyu. As an expert said, this kind of story happens in real life and is in accordance with China's legal guidelines [37]. However, despite improvements in legal and medical protection, it is still difficult to mitigate the loss of life chances in general and intimacy rights in particular of people living with HIV.

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Figure 1. A character not living with HIV expresses his feelings toward a character living with HIV (protagonist).

(Text in Picture) Qin Qin: Zheyu, I've always wanted to confess something to you: I have HIV.

(Text in Picture)) [A moment of silence] Jiang Zheyu: I don't mind, Qin Qin. I like you, and I want to be your boyfriend.

Internal Grammar of SKLWH

The external game grammar of SKLWH is built on its internal game grammar, including narrative elements and game materials. The narrative elements involve the following 4 aspects:

1. Game-character setting: The principle of setting characters is telling a complete story with only a few characters to make sure that the persuasion effect is not jeopardized by a lengthy game.
2. Game-structure layout: The classic structure of serious games is "trunk plots-branch plots-trunk plots," meaning that the game starts from the same (trunk) plot, enters different branch plots based on different decisions, and goes back to the trunk plot after the branch plots come to an end.
3. Decision-making setting: A decision-making plot is one where players enter different branch plots depending on their choices. Some decision-making plots are set to reflect the themes of serious games, while others are set to enhance playfulness. Figure 2 shows a decision-making plot where the protagonist must choose whether to move out of the dormitory when her HIV status is discovered by her roommates.
4. Ending setting: In interactive narrative games, players encounter many moments of decision-making, and different combinations of decisions lead to different plots and endings. In SKLWH, players' decisions eventually lead to 6 different endings, which condense the reflection on and breaking of HIV-related stigma.

Using the free materials in Cheng Guang's database, game developers without professional training can easily actualize game narratives by creating scenarios, dialogues, decision-making settings, special effects, and so on. Figure 3 shows the development process of the above interactive decision-making plot. Figure 4 illustrates how to input a dialogue during the game development process.

Figure 2. An instance of interactive decision-making in the game.

(Text in Picture)

A Try to explain to the roommates and hope they can understand.

B Feel hurt by the roommates' attitude and decide to move out.

Jia Jia:
Why are you so selfish? Why did you keep it a secret from us? Has it never crossed your mind that you might get us infected?

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Figure 3. Screenshot of the game in the process of being developed.

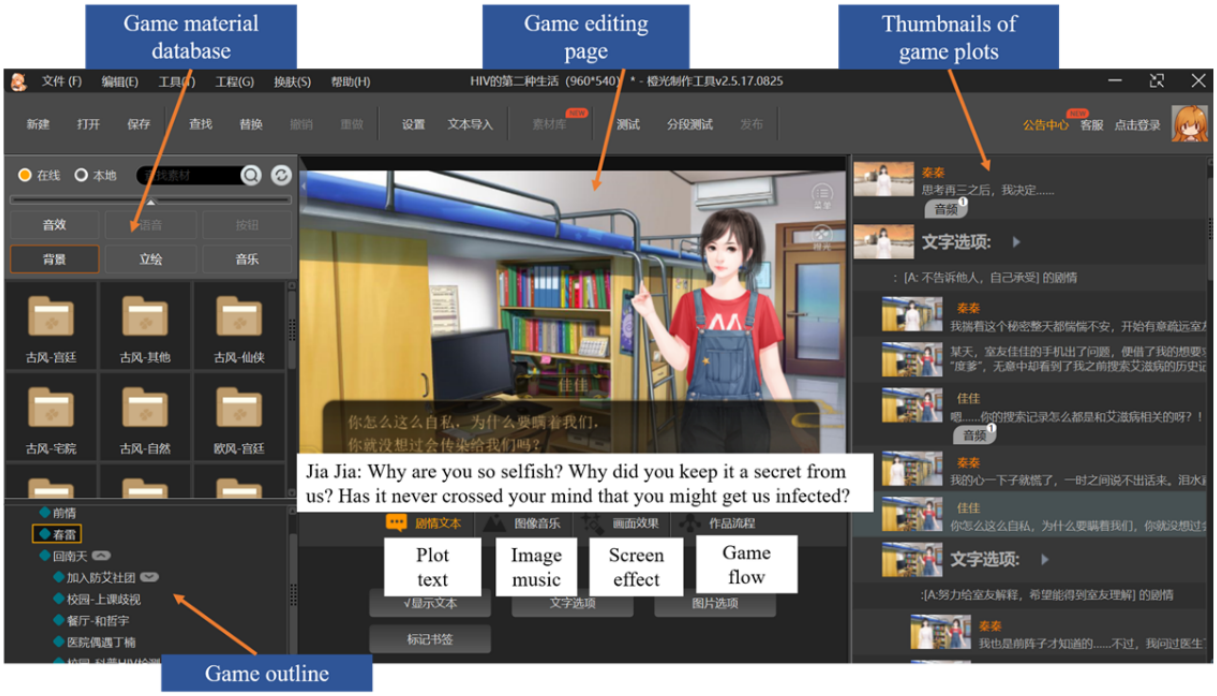

Figure 4. Dialogue input of the game in the process of being developed.

Participatory Serious Game Development Model

The section above briefly outlined the development process of SKLWH. Young students' active engagement in game development reflects the idea of "participatory culture" advocated by the communication scholar Henry Jenkins [38]. This idea entails that amateur developers participate as citizens, use technical platforms with low barriers to entry, and assume the responsibility of preventing and controlling HIV/AIDS through gamification.

Among the few HIV/AIDS education games in China, SKLWH is special because its development model can be popularized. It is a good example of the PSGDM proposed in this article (Figure 5). In this model, developers set the external game grammar by capturing important social issues and set the internal game grammar by means of narrative elements and game materials. The 2 grammars are combined in user-generated content game platforms, such as China's Cheng Guang, Yi Ci Yuan, and Tencent Games, as well as the overseas platform Steam. This means that the PSGDM can be used both inside China and abroad, allowing extensive community participation in game development and easy access to the public wishing to play the developed games.

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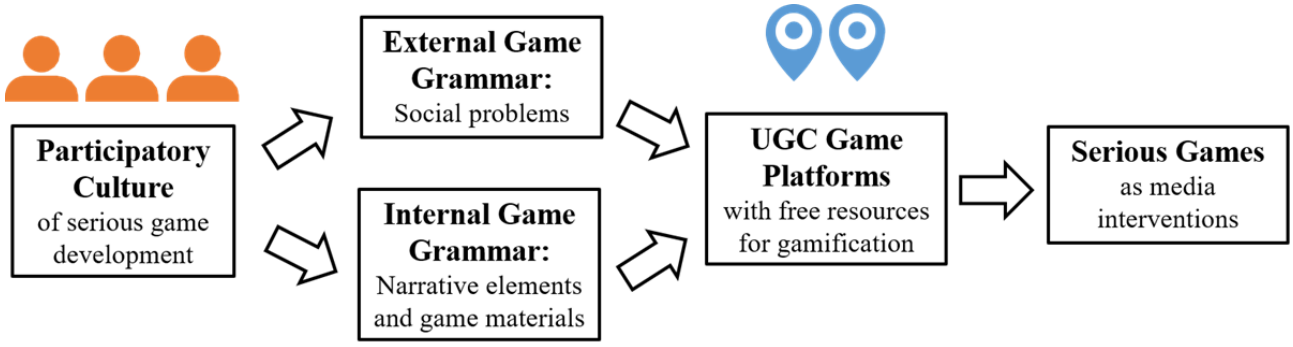
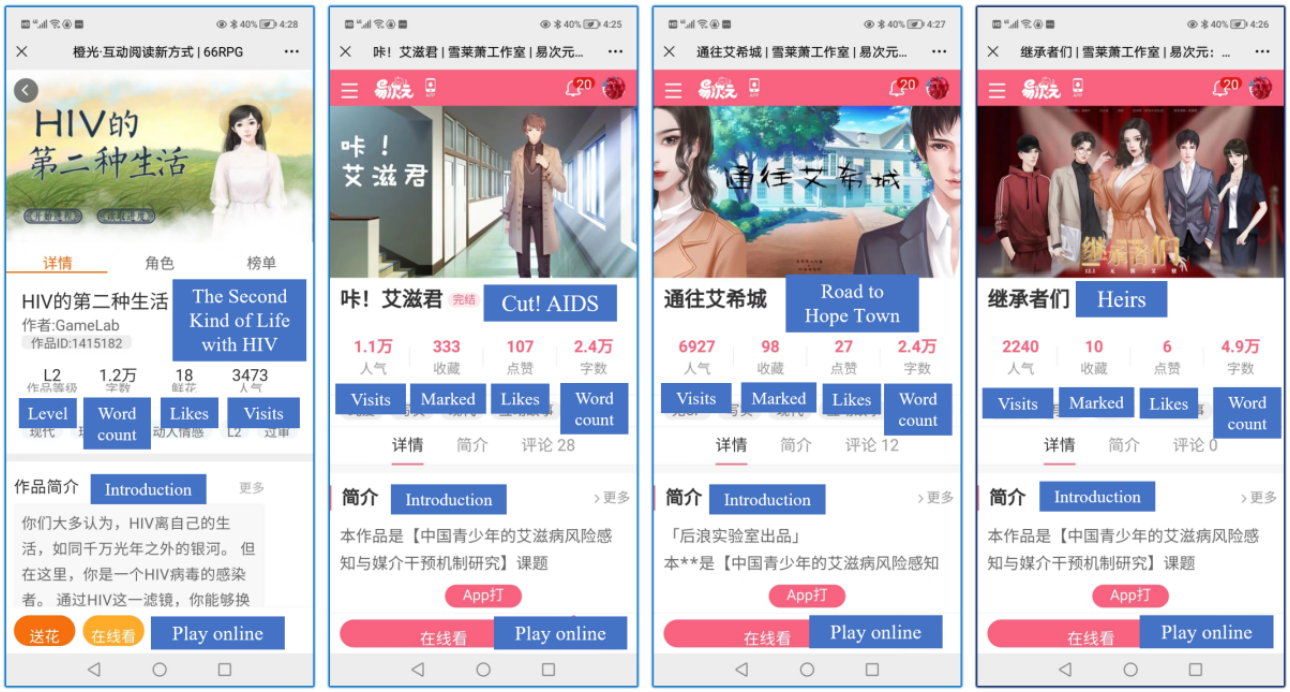
Figure 5. The participatory serious game development model. UGC: user-generated content.



Besides SKLWH, the team of the author XZ developed 3 other HIV-related games following the PSGDM and launched them on Yi Ci Yuan between 2020 and 2022, namely Cut! AIDS, Road to Hope Town, and Heirs (Figure 6). SKLWH is a love story, the protagonist of which is a female college student who has HIV. Cut! AIDS is a film-production story in which 3 male protagonists are infected with HIV or are at risk of HIV infection. These 2 games mainly reflect the HIV-related stigma against different groups. By telling a detective story, Road to Hope Town reflects not only external stigma toward people living with HIV but also the internalized stigma of people living with HIV. Reflecting HIV-related stigma as well as AIDS phobia, Heirs renarrates Road to Hope Town's detective story and allows players to identify with either a protagonist living with HIV or a protagonist not living with HIV. Regarding the external grammar, these 4 games work together to comprehensively reflect the complex dynamics of HIV stigma. Concerning the internal grammar, the playfulness of the love, film production, and detective stories was strengthened via interactive mechanisms, including decision-making, questions and answers, point rewards and punishments, clue search, and task accomplishment.

Figure 6. Mobile interfaces of HIV educational games developed based on the participatory serious game development model.



Experimental Evaluation Results

Degree of HIV-Related Stigma

First, the degree of HIV-related stigma in different dimensions was compared to explore if intimacy stigma is more evident than the other dimensions of stigma. Paired sample *t* tests (Table 2) showed that intimacy stigma (mean 2.58, SD 0.83) was far greater than morality stigma (mean 1.40, SD 0.46), with a significant difference between the 2 means (t_{139}=15.0; P<.001). Intimacy stigma was also greater than personal interaction stigma (mean 1.36, SD 0.55), with a significant difference between the 2 means (t_{139}=16.97; P<.001). However, there was no significant difference between the mean values of morality stigma and personal interaction stigma (t_{139}=0.76; P=.45).

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Table 2. Paired sample *t* tests of HIV-related stigma (N=140).

Variable	*t* value (*df*)	Difference between means	*P* value
Intimacy stigma-morality stigma	15.0 (139)	1.18	<.001
Intimacy stigma-personal interaction stigma	16.97 (139)	1.22	<.001
Morality stigma-personal interaction stigma	0.76 (139)	0.04	.45

Effects of Media Interventions

As HIV/AIDS interventions may not have the same effect on different genders [28], the impact of media interventions and gender on different dimensions of HIV-related stigma were explored by 2-way analysis of covariance. Chinese students usually get information about HIV/AIDS education from lectures and WeChat. Games are not a common channel, but once applied, they leave a deep impression. Therefore, the exposure frequencies of the 3 interventions were controlled as covariates. In terms of morality stigma, neither the interaction effect ($F_{1,133}$=0.05; *P*=.82) nor the main effect of media interventions ($F_{1,133}$=2.52; *P*=.11) was significant. The main effect of gender was significant ($F_{1,133}$=6.60; *P*=.01), with females' discrimination against people living with HIV (mean 1.29, SD 0.39) being lower than that of males (mean 1.50, SD 0.51). In terms of personal interaction stigma, the interaction effect ($F_{1,133}$=0.89; *P*=.35) was not significant. Furthermore, neither the main effect of media interventions ($F_{1,133}$=0.04; *P*=.85) nor that of gender ($F_{1,133}$=2.17; *P*=.14) was significant. Regarding intimacy stigma (Table 3), neither the interaction effect ($F_{1,133}$=0.38; *P*=.54) nor the main effect of gender ($F_{1,133}$=0.55; *P*=.46) was significant. However, the main effect of media interventions was significant ($F_{1,133}$=4.31; *P*=.04), and the effect of decreasing intimacy stigma was stronger in the game groups (mean 2.43, SD 0.84) than in the control groups (mean 2.73, SD 0.80). Thus, hypotheses 1, 2, 5, and 6 were verified. Intimacy stigma was the most severe among the 3 dimensions of HIV stigma. Females were more tolerant than males with regard to morality stigma, and the game intervention had an advantage in decreasing intimacy stigma. In all the analyses, the 3 covariates were not significant. The interactions were also not significant, and the effect of media interventions on all the dimensions of HIV-related stigma did not vary according to gender.

Table 3. Two-way analysis of covariance of intimacy stigma (N=140).

Variable	*F* value (*df*)[a]	*P* value
Pretrial lecture exposure	0.39 (1,133)	.53
Pretrial WeChat exposure	0.04 (1,133)	.84
Pretrial game exposure	0.41 (1,133)	.52
Media intervention	4.31 (1,133)	.04
Gender	0.55 (1,133)	.46
Media intervention × gender	0.38 (1,133)	.54

[a]Corrected total=139.

Group Discussion Results

Discussion Themes

The discussion themes were analyzed using NVivo (QSR International), which is a popular software for organizing, analyzing, and managing qualitative data [39], to explore the students' patterns of understanding (Table 4).

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Table 4. Focus group themes.

Theme and subtheme	Reference frequency, n (%)
Favorite education channel (N=56)	
Games (13 groups)	33 (58.9)
WeChat (10 groups)	18 (32.1)
Lectures (5 groups)	5 (8.9)
Defects of SKLWH[a] (N=56)	
Unattractiveness (5 groups)	9 (16.1)
Plot (6 groups)	22 (39.3)
HIV-related information (6 groups)	8 (14.3)
Interactivity setting (7 groups)	17 (30.4)
Advantages of SKLWH (N=51)	
Attractiveness (8 groups)	18 (35.3)
Game design (4 groups)	8 (15.7)
Educational effect (7 groups)	22 (43.1)
Innovation (3 groups)	3 (5.9)
Identification with the protagonist (N=42)	
Yes (9 groups)	28 (66.7)
No (7 groups)	14 (33.3)
HIV-related stigma (N=102)	
Morality stigma (12 groups)	28 (27.5)
Indiscreet behavior (9 groups)	15 (14.7)
Malicious transmission (8 groups)	13 (12.8)
Personal interaction stigma (10 groups)	23 (22.5)
Intimacy stigma (11 groups)	25 (24.5)
General statement (9 groups)	26 (25.5)
Internalized stigma (3 groups) (N=7)	7 (100)
Fear of people living with HIV (3 groups) (N=3)	3 (100)

[a]SKLWH: The Second Kind of Life with HIV.

Participant Narratives

Thematic coding indicated that the game intervention was more attractive to students. Among the 56 participants who answered the question regarding the favorite channel to receive HIV/AIDS education, 33 (59%) chose games, 18 (32%) chose WeChat, and 5 (9%) chose lectures. In the extracts below, 2 male participants from groups 7 and 13 explained their reasons for preferring games:

> *Personally, I prefer to choose games. [Games are] more interesting. Lectures can be very boring, and [I am usually] lazy in opening WeChat posts due to their low readability.* [Game intervention participant #29]

> *In my opinion, the most interesting form is games, because there is a sense of participation. If I have to rank [the channels], I will say games, WeChat posts, and lectures.* [WeChat intervention participant #18]

For some participants, SKLWH was unattractive. In their opinion, it required an improved plot, more useful HIV-related information, and better interactivity settings. However, these participants compared SKLWH to commercial games from the entertainment industry rather than to other HIV educational tools. Those participants who liked the game praised its plot and educational effects. SKLWH was also sometimes praised for its innovation in the field of HIV/AIDS education. A female respondent in group 3 made the following comment:

> *This game largely appealed to me. In contrast, the lectures on HIV/AIDS education that I heard before were very boring. The game is useful to disseminate HIV-related information through storytelling.* [Game intervention participant #11]

"What kinds of situations are people living with HIV facing in society?" was a broad question that allowed participants to answer according to their understanding. Many participants discussed various kinds of stigma faced by people living with

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HIV. They also described the behavior of people living with HIV as indiscreet and criticized "some" people living with HIV for maliciously spreading HIV on purpose. Ignored by previous studies, "malicious transmission" is also an indicator of morality stigma. This can be shown through the following dialogue between 2 female participants in group 1:

> *There are some [people living with HIV], especially those who are anti-social* [persons]…[Game intervention participant #1]
>
> *They do not confess [their HIV-positive status] and intentionally have unprotected sex to disseminate HIV.* [Game intervention participant #3]
>
> *That's right.* [Game intervention participant #1]

As mentioned earlier, the paired sample *t* test showed that intimacy stigma was significantly greater than morality stigma and personal interaction stigma. Indeed, the impossibility of intimacy was "a matter of principle" for some participants, as shown by the following explanation offered by a male student in group 3:

> *People living with HIV are discriminated at the social level. As far as I am concerned, I do not discriminate against people living with HIV and can accept them, but [I'm a person] with principles and a baseline.* [Game intervention participant #10]
>
> *Could you please explain what constitutes a matter of principle for you?* [Researcher]
>
> *For example, I don't discriminate against people living with HIV and can dine with them, but it is unacceptable to have a romantic relationship [with them].* [Game intervention participant #10]
>
> *This is a principle for you.* [Researcher]
>
> *Some people may think I discriminate against people living with HIV.* [Game intervention participant #10]
>
> *[The intimacy issue] was raised in the questionnaire.* [Researcher]
>
> *Yes, I cannot cross that line, that is, I cannot accept [having romantic relationships] with people living with HIV. But I am not a person who discriminates against people living with HIV.* [Game intervention participant #10]

The dialogue below between 1 female and 2 male students in group 10 reflects morality stigma, personal interaction stigma, and intimacy stigma simultaneously.

> *I think it does not matter for me to have everyday interactions or communications with people living with HIV, as long as [intimate relationships] are not concerned.* [WeChat intervention participant #5]
>
> *As far as I am concerned, I can have personal contacts [with people living with HIV]. But if my relatives and friends knew it, they would say, "Oh, how dare you stay with those people living with HIV? Don't you worry about being infected?" Then, I may not dare to have interactions [with people living with HIV].* [WeChat intervention participant #4]
>
> *As regards romantic relationships with people living with HIV and so on, as listed in the questionnaire, I am quite unwilling to have them. But it is okay for me to have common interactions. Moreover, in the opinion of most people, HIV infection means that people living with HIV are indiscreet in their private life.* [WeChat intervention participant #2]

Regarding identification, 67% (28/42) of the related narratives were about the identification experience with the character living with HIV, while 33% (14/42) were not. A female student in group 4 described her feelings when playing the game:

> *I had a sense of identification. I hesitated a little when making choices. I imagined what I would choose if I were the female protagonist.* [Game intervention participant #18]

It is worth noting that some participants reported complicated game experiences, as they sometimes identified with Qin Qin and sometimes did not. Game intervention participant #12, another female student in group 4, regarded herself as unidentified. However, she followed the plot and carefully considered the interactive decisions. Therefore, identification is an important construct and should be explored in future studies of the stigma-decreasing effect of game interventions.

Discussion

Principal Findings

In the past, when intervention mechanisms, such as serious games, were expected to reduce HIV-related stigma, the stigma was usually viewed as a whole. It was unclear which dimensions of HIV stigma could be alleviated by games or other factors. By closely examining 3 dimensions of HIV stigma, this research found that females have a more tolerant attitude than males in the dimension of morality stigma. With regard to decreasing personal interaction stigma, no significant difference was found between the 2 genders or the 2 media interventions. The game intervention had a greater effect in reducing intimacy stigma, which was strong and difficult to mitigate, with both genders' attitudes remaining conservative regarding this issue. The nonsignificant interaction effect demonstrates that the effect of media interventions does not vary with gender. Accordingly, our focus should not be on designing different versions of educational content for each gender but on decreasing different dimensions of HIV-related stigma with the most effective media intervention, such as using games to decrease intimacy stigma.

By providing in-depth information, the findings of the group discussions validated the results of the quantitative analysis. Intimacy stigma was much more severe than morality stigma or personal interaction stigma. The impossibility of intimacy is a principle that was often expressed by participants when considering their relationships with people living with HIV. The game intervention was largely praised in terms of HIV/AIDS education, though SKLWH did not satisfy all participants. According to some of them, one of the main defects of the game was the optimistic description of the life of a person living with HIV, especially the romantic relationship between the protagonist living with HIV and the character not living

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with HIV. In their view, this kind of life is abnormal and unrealistic. In fact, this criticism reflects the deep discrimination against people living with HIV. Instead, SKLWH hopes to publicize that people living with HIV can live a normal life, that is, a second life different from that imagined by the public.

Furthermore, to advance research beyond individual cases, this study provides the following insights into the development of serious games. First, this research is an example of the development and effect evaluation of HIV/AIDS educational games in China, which can encourage more relevant practices in the future. Second, the PSGDM proposed in this study can promote a participatory culture for developing serious games by those dedicated to health communication and media interventions. Third, as an interdisciplinary study on communication and medicine, this research shows that HIV/AIDS prevention or control is not the duty of only medical experts and that serious game development is not the responsibility solely of game experts. More people can be engaged in and share the responsibility of health education.

Strengths and Limitations

This study linked game development and effect evaluation; it used a mixed methods evaluation to achieve data triangulation and combined causality verification and in-depth explanation. SKLWH and 3 other games developed by the team of the first author XZ help fill the gap in web-based gaming tools for HIV/AIDS education in China. With around 26,000 visits to date, the 4 games have tried to extend their educational effect among young people. Although the games are far from perfect, the gamification practices based on the PSGDM are very promising.

The team was not very experienced when they developed SKLWH, and the game is thus relatively simple in form and not sufficiently entertaining. As a result, the desired persuasive effect on attitudes based on the EORM has not been fully realized. The measurement of HIV-related stigma also needs improvement, and the reliability of morality stigma in this study was not high enough. The HIV-related stigma scale should be modified in light of current social mentalities and concrete contexts. Future studies may consider including the malicious consciousness of HIV transmission of people living with HIV as an indicator of morality stigma, as suggested in the group discussions. Moreover, controlling the theoretical variables could lead to a better analysis of the mechanisms in the game's effect.

Comparison With Prior Work

One of the few effect evaluations of HIV/AIDS educational games in China found that the hero combat game AIDS Fighter · Health Defense did not have a significant effect on decreasing HIV-related stigma [40]. The researchers suggested that the decrease in stigma may need time to take effect. In addition, we should also notice the differences among various types of serious games. Racing games, board games, card games, hero combat games, and narrative games are all applicable to HIV/AIDS education. However, narrative games may have a greater effect on mitigating stigma owing to their narratives and mechanisms, such as empathy, identification, and transportation [24].

Conclusions

Among the different methods of HIV/AIDS education that target young students, games are a feasible and highly acceptable choice. Due to the lack of a cure and an effective vaccine for AIDS, this disease needs games and other forms of media interventions more than other infectious diseases. More effort should be made in serious game development for HIV/AIDS education, and SKLWH is one of the few results of this effort in China. By leveraging free resources on digital platforms, new media users can develop games for health education by themselves, thereby enabling extensive social engagement in HIV/AIDS prevention and control. People living with HIV experience being regarded as "others." Society rejects them, and sometimes they even reject themselves. If this problem remains unsolved, it could cause difficulties in the treatment, prevention, and control of HIV/AIDS. The suffering of "others" leads to the regression of society. We need more serious games to allow players to empathize with people living with HIV and reflect on HIV-related stigma. Only this can allow us to completely break the metaphor of "others."

Acknowledgments

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Conflicts of Interest

None declared.

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Abbreviations

EORM: entertainment overcoming resistance model
PSGDM: participatory serious game development model
SKLWH: The Second Kind of Life with HIV

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Original Paper

An Automated Virtual Reality Training System for Teacher-Student Interaction: A Randomized Controlled Trial

Seth King[1], PhD; Joseph Boyer[2], MA; Tyler Bell[2], PhD; Anne Estapa[1], PhD

[1]Department of Teaching and Learning, College of Education, University of Iowa, Iowa City, IA, United States

[2]Department of Electrical and Computer Engineering, College of Engineering, University of Iowa, Iowa City, IA, United States

Corresponding Author:
Seth King, PhD
Department of Teaching and Learning
College of Education
University of Iowa
240 S. Madison St.
Iowa City, IA, 52242
United States
Phone: 1 828 448 0950
Email: sakng@uiowa.edu

Abstract

Background: Shortages in qualified supervision and other resources prevent education personnel from rehearsing effective practices. Interactive simulations, although increasingly used in education, frequently require instructor management. Automated simulations rarely engage trainees in skills related to practice (eg, speech).

Objective: We evaluated the capability of delivering behavioral skills training through an automated virtual reality (VR) simulation using artificial intelligence to improve the implementation of a nondirective mathematical questioning strategy.

Methods: We recruited and randomly assigned 30 college-aged participants to equivalent treatment (ie, lecture, modeling, and VR; 15/30, 50%) and control groups (ie, lecture and modeling only; 15/30, 50%). The participants were blind to treatment conditions. Sessions and assessments were conducted face to face and involved the use of VR for assessment regardless of the condition. Lessons concerned the use of a nondirective mathematical questioning strategy in instances where a simulated student provided correct or incorrect answers to word problems. The measures included observed and automated assessments of participant performance and subjective assessments of participant confidence. The participants completed the pretest, posttest, and maintenance probes each week over the course of 3 weeks.

Results: A mixed ANOVA revealed significant main effects of time ($F_{2,27}$=124.154; P<.001; η_p^2=0.816) and treatment ($F_{1,28}$=19.281; P<.001; η_p^2=0.408) as well as an interaction effect ($F_{2,28}$=8.429; P<.001; η_p^2=0.231) for the average percentage of steps in the questioning procedure. Posttest scores for the intervention group (mean 88%, SD 22.62%) exceeded those of the control group (mean 63.33%, SD 22.64%), with t_{28}=3.653, P<.001, and Cohen d=1.334. Maintenance scores indicated a positive effect of the intervention (mean 83.33%, SD 24.40%) relative to the control (mean 54.67%, SD 15.98%), t_{28}=3.807, P<.001, Cohen d=1.39. A Mann-Whitney U test indicated that the treatment groups' self-ratings of confidence (mean 2.41, SD 0.51) were higher than those of the control group (mean 2.04, SD 0.52), U=64, P=.04, r=0.137.

Conclusions: The results demonstrate the potential of artificial intelligence-augmented VR to deliver effective, evidence-based training with limited instructor management. Additional work is needed to demonstrate the cascading effect of training on authentic practice and to encompass a wider range of skills.

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KEYWORDS

virtual reality; artificial intelligence; behavioral skills training; education; professional development; staff training; mathematics

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Introduction

Background

High-quality professional development contributes to the effectiveness of education personnel [1] and success of their students [2]. However, the training education professionals receive before entering the field often consists of lectures [3] with few opportunities to practice skills or receive performance feedback—key aspects of effective professional development [4-6]. Training ideally provides multiple opportunities for practice across a range of unpredictable situations under the supervision of a competent observer [7]. The prevalence of less effective approaches to professional development stems from a shortage of qualified supervisors and suitable practicum placements in many areas [6,8]. The difficulty in providing effective training for education personnel has perpetuated the use of ineffective practices in education [9].

Head-mounted virtual reality (VR) using an array of visual, auditory, and tactile interfaces that adjusts the display based on user sensorimotor inputs to fully immerse participants within a simulation [10] is increasingly associated with improved learner outcomes, increased engagement, and the ability to repeatedly practice skills [11,12]. The immersion permitted by VR potentially allows educators to engage in behaviors and interact with stimuli closely aligned with actual practice, which can potentially improve the administration of instruction and increase teacher confidence [13]. The maximum immersion permitted through VR may not be necessary in all scenarios (eg, conversation); however, VR allows for a realistic representation of nonverbal communication that accompanies speech as well as any potential physical interactions. In addition, *removing* components from a fully immersive simulation to place core content on platforms such as desktops is technically easier than *adding* critical immersive elements to simulations developed on less-sophisticated devices [14]. VR applications can be adapted to preserve their core functionality across a range of devices, thus making development on the platform potentially conducive to dissemination.

The technology associated with VR has become more affordable [15]; however, it is most frequently used as a training tool in medicine [16]. The results of VR simulations tested in the educational context are mixed, with early reports of limited effectiveness and induced illness [15] being contradicted only by recent research with more positive findings [17]. VR simulations specific to teacher education typically require trainees to observe events depicted in 3D space (eg, bullying behavior and self-injury) rather than interact [13,18]. VR simulations targeting human interaction are typically controlled directly by expert trainers; at a minimum, human observers must administer assessments [13]. Experiments involving the performance of complex procedures (eg, functional communication training [19]), although they include scripts to simulate the behavior of student avatars, rely on researchers to assess trainees.

Although absent from studies of teacher training, artificial intelligence (AI)—or software capable of independently acquiring, processing, and acting upon information [20]—is emerging as a force in education through the growing implementation of chatbots, automated assessment, facial recognition, and other functions to support teaching and learning [21]. AI relies on machine learning (ie, natural language processing) in which computers are trained to classify new stimuli following exposure to previous data sets (ie, training data) and statistical models to make predictions based on new information [22]. Intelligent tutoring systems, which provide individualized instruction based on the responses and characteristics of learners, encompass many AI functions relevant to education, including learner assessment, content generation, and providing feedback [23]. An increasing number of programs targeting specific academic skills in K-12 and higher education have recently emerged [22], such as the IBM Watson Tutor, a dialogue-based tutor that uses natural language processing to interpret learners' comments and provide appropriate feedback [24]. However, studies integrating VR and AI are currently limited [22]. Existing applications incorporating AI, such as Lamb and Etopio's classroom management scenarios [25], allow for participant interaction with student avatars but do not assess the implementation of discrete instructional practices.

A recent experiment [14] demonstrated the effectiveness of an automated VR simulation capable of administering instructional procedures and assessing learner performance on the use of a mathematical questioning procedure. Evidence suggests that nondirective mathematical questioning, in which students' thought processes are elicited before confirming whether an answer is correct, can improve student outcomes [26]. Effective questions require students to assess, explain, and justify their answers [27]. This process facilitates instructional decisions, especially when teachers cannot observe the problem-solving process or the correct answer may be derived through an inefficient or inappropriate approach [28]. Interaction-focused techniques such as mathematical questioning, which involves the assessment of speech rather than simple movements or button presses, differ from the content generally addressed in VR training simulations.

The training developed by King et al [14] consisted of video-recorded lectures and simulations capable of providing automatic assessment, textual prompting, and feedback through the incorporation of VR and AI (eg, speech classification and speech-to-text). As in the research conducted by Clay et al [19], the components of the intervention were arranged in accordance with behavioral skills training (BST), an evidence-based approach to personnel preparation encompassing a range of instructional components, including didactic instruction, modeling, rehearsal, and feedback [29,30]. Textual onscreen prompts, systematic prompting, and video models were incorporated based on evidence of their effectiveness in the literature [31-33]. The use of a single-case design [34-36] permitted improvements in simulation functionality over the course of the experiment, resulting in automated assessments with a high degree of agreement with direct observation (>96%) and large changes in the percentage of steps in the procedure exhibited by the two participating trainees after 3 consecutive days of training (Tau_{bc}=0.80 [37]).

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In contrast to many approaches to VR, which are not constructed in accordance with a specific learning theory [38], the simulation developed by King et al [14] was predicated on behavioral theories of learning and instruction [39] that aim to encourage appropriate responses in the presence of specific antecedents (ie, discriminative stimuli), for example, praising a student for correctly answering a math problem. The ability of an antecedent to evoke the correct response can be increased and sustained through the introduction and gradual fading of prompts. Instructors may also administer consequences designed to increase correct responses, which can include providing stimuli of value to the learner (ie, positive reinforcement) or allowing the learner to avoid unpleasant stimuli (ie, negative reinforcement) [39]. Prompts and consequences are most effective when provided immediately. In King et al [14], the responses generated by simulated students represented antecedents associated with the correct steps of a procedure. The participants received textual prompts before they had an opportunity to respond. In addition, the simulation provided correctives immediately following incorrect responses and required the participants to provide a correct response. The avoidance of corrective procedures upon the use of correct responses in subsequent sessions and feedback regarding correct answers following each session provided negative and positive reinforcement, respectively. Notwithstanding this theoretical basis and the positive findings associated with the simulation, the small sample size and iterative development that occurred over the course of the experiment represent clear limitations.

Purpose

Given the scarce resources available for training, a simulation capable of independently providing assessment and instruction related to student-teacher interaction has the potential to benefit education personnel as well as their students and result in the wider dissemination of professional development. In light of the limitations of earlier work in this area [14], this study assessed the ability of a feature-locked, AI-enhanced VR training application to independently impart the steps of a mathematical questioning strategy using a randomized controlled design. The guiding questions included the following: (1) Compared with individuals who did not receive training in VR, does the simulation improve the participants' acquisition of steps in a mathematical questioning strategy? (2) To what extent does group performance differ during maintenance (ie, extended absence of instruction) and generalization (ie, untaught items) probes? (3) Does the VR simulation increase the participants' perceived confidence in the use of the procedure, relative to the control group? (4) To what extent do the observed measures of trainee performance correspond with the automated measures?

Methods

Ethics Approval

The university institutional review board at the University of Iowa approved all procedures and consent forms before recruitment (202112205).

Participants and Setting

Recruitment began in January 2022. The study was conducted throughout March and April 2022. Eligible participants were current and former graduate and undergraduate students affiliated with the University of Iowa. Potential participants were (1) aged >18 years; (2) free of seizure disorders, epilepsy, or other health conditions potentially exacerbated by VR; and (3) able to use voice-activated assistants such as Alexa without accommodations. In addition, we excluded participants who were likely to be familiar with the subject material (ie, participants with employment experience in an educational setting or participants with records of completing courses in mathematics education) to ensure sufficient sensitivity to the intervention. A US $15 gift card was offered as an incentive for participation. For recruitment, the second author described the study to students in cooperating classrooms; the participants were also encouraged to share information regarding the study with potentially interested peers. In total, 30 individuals agreed to participate in this study. We assigned the participants to the experimental groups using a stratified randomization [40] procedure based on observed mastery probes (OMPs) during the baseline phase. No attrition occurred over the course of the study. A survey of participant characteristics revealed no significant differences in familiarity with VR before the experiment. Additional demographic characteristics of the participants are shown in Table 1.

Sessions and assessments were administered face to face in a small room with computer and internet access. Each participant's sessions occurred once per week for 3 consecutive weeks. Scheduling ensured that approximately 7 days elapsed between the assessment sessions, which otherwise occurred at times acceptable to the participants. The participants were advised to terminate the sessions at the first sign of discomfort; however, all the sessions were completed without any incident. A master's-level student in computer engineering (ie, the session administrator) conducted all the sessions with the participants individually.

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Table 1. Participant demographics.

Participant	Total (N=30)	Control (n=15)	VR[a] (n=15)
Age (years), mean (SD); range	22.13 (1.5); 19-26	21.87 (1.81); 19-26	22.4 (1.12); 21-25
Sex[b], n (%)			
Male	16 (53)	8 (53)	8 (53)
Female	14 (47)	7 (47)	7 (47)
Academic program, n (%)			
Business or finance	8 (27)	4 (27)	4 (27)
Engineering	13 (43)	6 (40)	7 (47)
Other	9 (30)	5 (33)	4 (27)
Educational status, n (%)			
Undergraduate	15 (50)	9 (60)	6 (40)
Masters	6 (20)	2 (13)	4 (27)
Doctoral	2 (7)	2 (13)	0 (0)
Other	7 (23)	2 (13)	5 (33)
VR experience[c], mean (SD); range	4.47 (1.74); 1-6	4.47 (1.73); 1-6	4.47 (1.81); 1-6

[a]VR: virtual reality.

[b]None of the participants identified as being nonbinary.

[c]VR experience was determined using a 6-item Likert-type scale ranging from 1 (no experience) to 6 (much experience).

Materials

A commercially available Windows (Microsoft Corp) desktop computer facilitated video playback. We used the Oculus Quest 2 (Facebook Reality Labs; US $300) VR headset and its 2 controllers for all the instructional simulations. The Quest device has an integrated microphone and speakers and tracks motion without external sensors.

Dependent Variables

Overview

This study examined 6 distinct dependent variables. The observed percentage of lesson steps completed correctly (ie, OMP) represented the principal outcome. To evaluate the simulation's assessment capabilities, we compared the results of the OMPs with those of a virtual mastery probe (VMP) assessing the same skills. We obtained additional information regarding the perceptions of the participants from the SKIL Survey [41].

OMP Assessment

For the OMPs, the session administrator collected information regarding the percentage of steps in the questioning procedure that the participants completed while interacting with the student avatar in the VR simulation. We calculated the results in terms of the total number of steps performed correctly divided by the total number of steps in procedures taught in lessons 1 and 2 combined (ie, 10 steps). The OMPs were created in relation to the content taught during training (ie, *acquisition* probes) to assess the participants across the baseline, posttest, and maintenance sessions as well as untaught content to assess the generalization of the procedure in posttest and maintenance sessions (ie, *generalization* probes). The steps in the acquisition probe are shown in Table 2 (refer to "teacher steps"). We scored the OMPs in accordance with the single-opportunity method, in which the probe ended as soon as the participant exhibited an incorrect response [42] because of (1) concerns regarding time commitment and (2) the chance of skill acquisition in the absence of instruction. Research suggests that single-opportunity method probes of chained tasks contribute relatively little bias [42]. The participants did not receive feedback following the completion of the OMPs.

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Table 2. Steps in lessons 1 and 2 for teachers and simulated student.

Step	Description	Example and variations
Lesson 1: responding to a correct answer		
T1[a]: read the problem	The teacher reads the problem clearly and without errors	• "You have 5 fishbowls with 4 fish in each bowl. How many fish are there total?"
S1[b]: brief student correct answer	The student provides the correct answer without additional detail	• "There are 20 fish." • "The answer is 20."[c]
T2: unpack strategy request (correct)	After the student provides the correct answer, the teacher asks the student to explain	• "How did you solve this problem?" • "Why is that the answer?"
S2: student unpacks correct strategy	The student describes the appropriate method they used for answer	• "I multiplied 5 times 4." • "I took 5 and 4 and multiplied."
T3: Praise	The teacher praises the student's effort	• "Good job." • "Nice job, buddy."
Lesson 2: responding to an incorrect answer		
T1: read the problem	__[d]	—
S1: brief student incorrect answer	The student provides an incorrect answer without additional detail	• "I don't know. Nine fish?" • "It's nine fish I think."
T2: unpack strategy request (incorrect)	After the student provides an incorrect answer, the teacher asks the student to explain	—
S2: student unpacks incorrect strategy	The student describes the inappropriate method they used for answer	• "I added 5 plus 4." • "I used addition."
T3a: underscore task feature (strategy)	The teacher asks why the student used a specific incorrect strategy	• "What in the problem made you add?" • "Tell me why you used addition."[e]
S3: strategy explication	The student describes why they used an incorrect strategy	• "Well, you said there were 5 fishbowls and 4 fish." • "I didn't know what to do, so I added."
T3b: underscore task feature (problem)	The teacher prompts the student to re-examine the problem	• "What is the problem asking you to do?"
S4: feature identification	The student proposes a new approach based on the problem features	• "I see. I need to count the fish in all of the bowls." • "I need to add five '4s' together."
T4: teacher grouping request	The teacher asks the student to attempt the problem again	• "What would your answer be now?" • "Can you try solving again?"
S5: brief student correct answer	The student provides the correct answer without additional detail	• "You would have 20 fish then." • "The answer is 20."
T5: unpack strategy request (correct)	—	—
S6: student unpacks correct strategy	—	—
T6: praise	—	—

[a]T: teacher.

[b]S: student.

[c]To prevent rote responding, the students provided varied responses for each step. Some examples are not exhaustive.

[d]The content is identical to previous version of the step.

[e]Variations for teachers refer to potentially correct examples. Examples are not exhaustive.

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SKIL Survey

We assessed the respondents' stated understanding of questioning using an adapted version of the SKIL Survey [41]. The survey consisted of concepts rated across three scales: (1) *knowledge* of the content, (2) *confidence* in the use of the techniques, and (3) perceived *usefulness*. The respondents rated the items using a 4-point Likert-type scale ranging from 0 (eg, *no knowledge*) to 3 (eg, *substantial knowledge*). We presented a small sample of eight assessment items because of the narrow focus of the training. Surveys featuring a reduced number of items obtained acceptable internal consistency in previous studies, with a Cronbach α for knowledge of .907, confidence of .882, and usefulness of .915 [13]. We delivered instructions regarding the purpose of the assessment before each administration. The participants completed the SKIL Survey during the baseline and maintenance sessions.

VMP Assessment

The VMP and OMPs were administered concurrently to determine the correspondence between the simulation-administered assessments and direct observations conducted by a human. The VMP assessed the exact same steps in the procedure as the acquisition and generalization OMPs via the speech classifier embedded in the simulation, which (1) recorded textual output corresponding to a participant's spoken response, (2) determined whether the text's classification matched the classification of correct responses for each step, and (3) calculated the percentage of correct steps completed by the participant.

Design

We analyzed the effectiveness of the intervention using a single-blind, independent measures pretest-posttest design. The participants were placed in an intervention condition (ie, lecture, model, and VR practice) or a control condition (lecture and model only) using stratified random assignment [40] based on baseline OMP scores. Randomization was achieved using Microsoft Excel. The identities of the participants were concealed from the researchers during the randomization process.

Simulation

The VR simulation featured in this study was developed over the course of 2 years by an interdisciplinary team consisting of faculty in behavior analysis, math education, and computer engineering. A task analysis [39] of mathematical questioning was conducted to identify the teacher and student actions emitted during applications of mathematical questioning. In a departure from the typical task analysis procedure, we created different lessons based on likely student responses. The initial analysis included many possible variations accounting for student actions such as nonresponses. This became the basis for the skills evaluated in this study: (1) responding to a correct answer and (2) responding to an incorrect answer (ie, lessons 1 and 2). An example of the flowcharts resulting from this process that illustrate the possible sequences of events in a scenario, as well as sequences in lessons 1 and 2, are shown in Figure 1. Table 2 describes the specific steps in each lesson.

The simulation corresponding to the mathematical questioning procedure consisted of multiple components. A custom React [43] web application permitted the generation of simulation content (eg, steps in a procedure), which was stored in a database for retrieval by the simulation. Figure 2 depicts the web application used to generate flowcharts, allowing for different lessons based on the anticipated student responses. The application further allowed for the generation of reports regarding the performance of the participants (Figure 3). The simulation, developed in Unity (Unity Technologies), allows trainees to interact with a virtual student in a simulated classroom environment. All VR assessments and instructional sessions across experimental conditions began with the participant verbally presenting the student avatar with a math problem involving multiplication before deviating into different pathways based on the initial student response. A depiction of the start of a typical simulation and user prompt is shown in Figure 4. We trained the speech classification AI to recognize the topographical variations of potential participant statements. The key technical aspects of this work include (1) the ability of the virtual student to speak to the participant, (2) the ability of the participant to vocally respond to the virtual student, and (3) the ability of the simulation to classify the participant's responses as correct or incorrect.

Speech from the student avatar was accomplished using IBM Watson's [44] Text-to-Speech, which converted text strings corresponding to predetermined student responses into audio data. To promote the extent to which trainees responded correctly to distinct student statements that should nonetheless evoke a similar step in the procedure (eg, incorrect response; nonresponse) [45], student avatar responses at each step were drawn from functionally identical yet topographically dissimilar text strings. Examples of the student statements are listed in Table 2.

Assessment of the trainees' responses was accomplished using IBM's Speech-to-Text, which converted the trainees' statements into a text string, and the Google Natural Language AI service [46], which determined whether a trainee's transcribed statement matched the targeted response for a specific step of the procedure. The text classifier was trained using phrases corresponding to each step of the simulation (Table 2). After training, the classifier could be used to identify novel text strings that did not perfectly match the training phrases. This allowed the simulation to accommodate variability in the trainees' responses. The classifier would provide a confidence value between 0.00 and 1.00, specifying the degree to which the provided text corresponded to each step of the procedure. Higher values reflected a greater degree of confidence in a statement's correspondence to the phrases included in the training. We established a classifier threshold (eg, 0.75) to determine how closely the participants' responses needed to match the expected response at each step. If the classification confidence exceeded the threshold, the system identified the participants' responses as correct.

When combined with recorded lectures describing the rationale for a procedure and a model of the procedure's delivery, the use of the VR simulation comprised a computer-mediated form of BST. Resources associated with the appropriate delivery of

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BST have often prevented its use in practice [47]. Consequently, automating instructor-intensive portions of the practice may assist in disseminating effective training practices.

Figure 1. Flowcharts depicting example of appropriate sequence of events in a scenario (top), steps in lesson 1 (middle), and steps in lesson 2 (bottom).

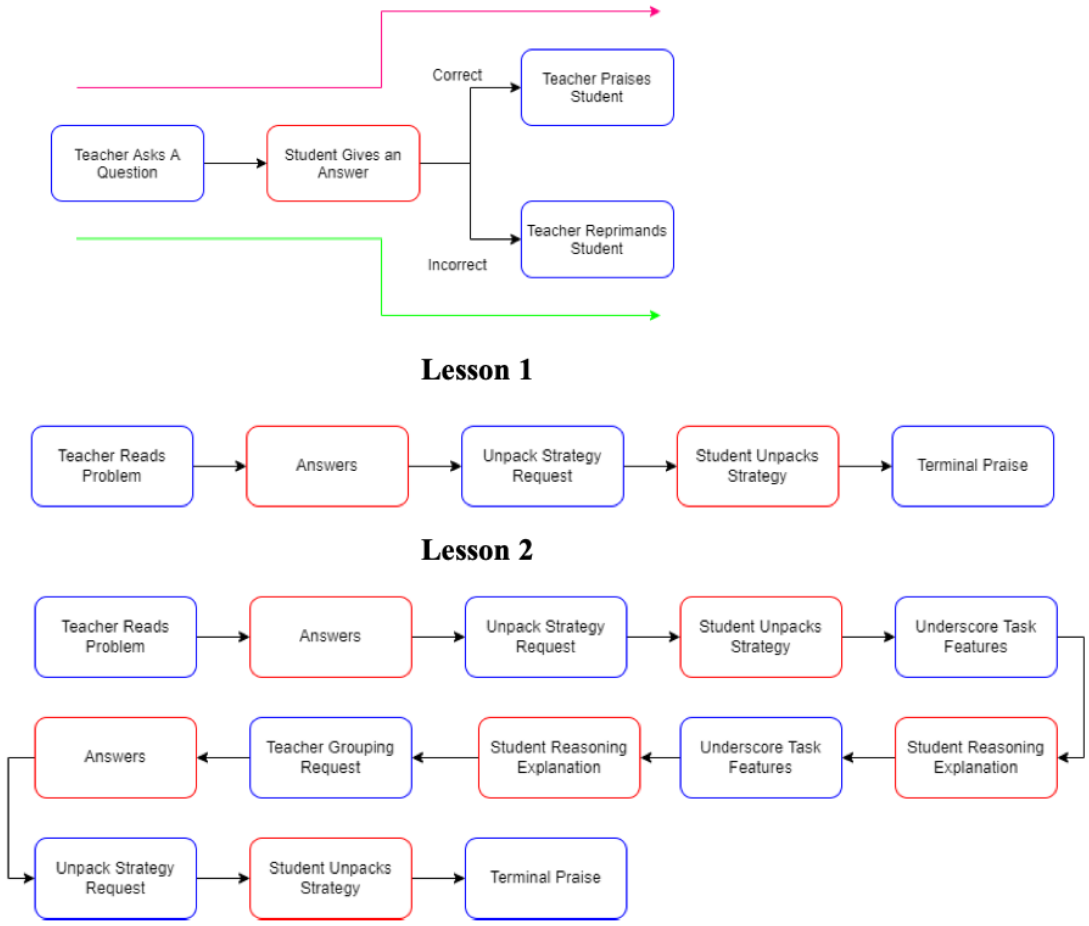

Figure 2. Web application page depicting tools used to design flowcharts and novel lessons. Lesson creation provides a drag and drop interface to allow the creation and connection of nodes for a flowchart. In addition, classifications can be assigned to each node. Once the flowchart is completed, the lesson creation page also allows the user to create individual lessons needed to run a simulation. VR: virtual reality.

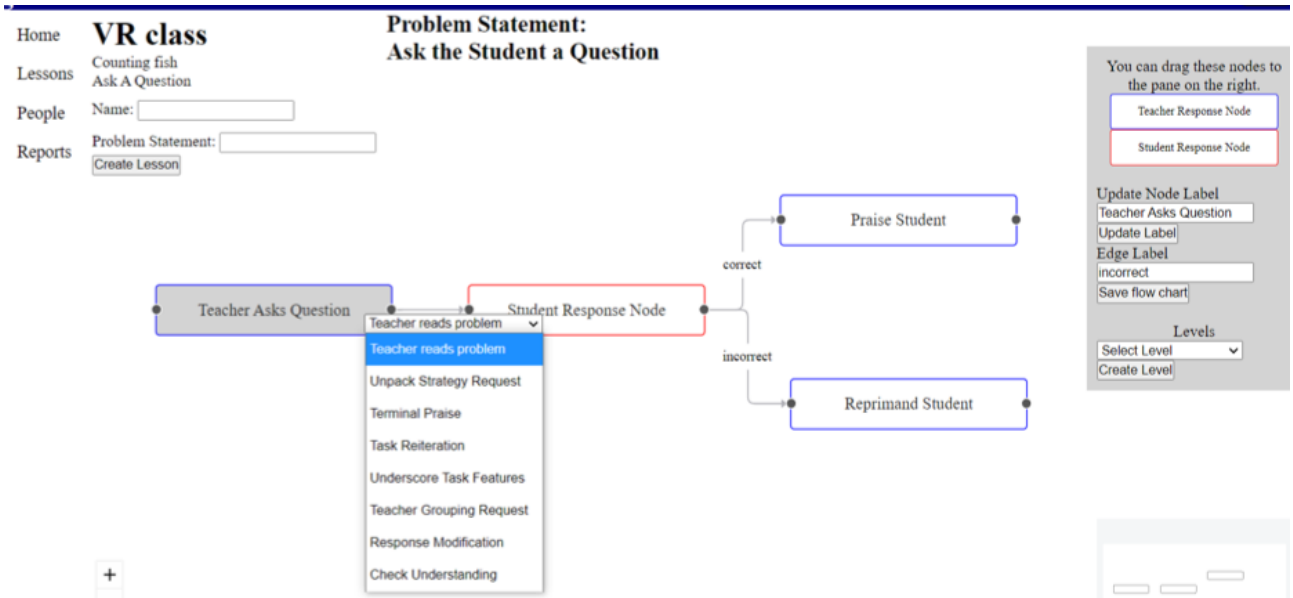

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Figure 3. Reports page depicting simulation feedback. The report includes all the information recorded by the simulation feedback. Having reports accessible allows the instructors to create personalized analyses for each trainee and create a profile to determine how effectively the trainee understands the presented material.

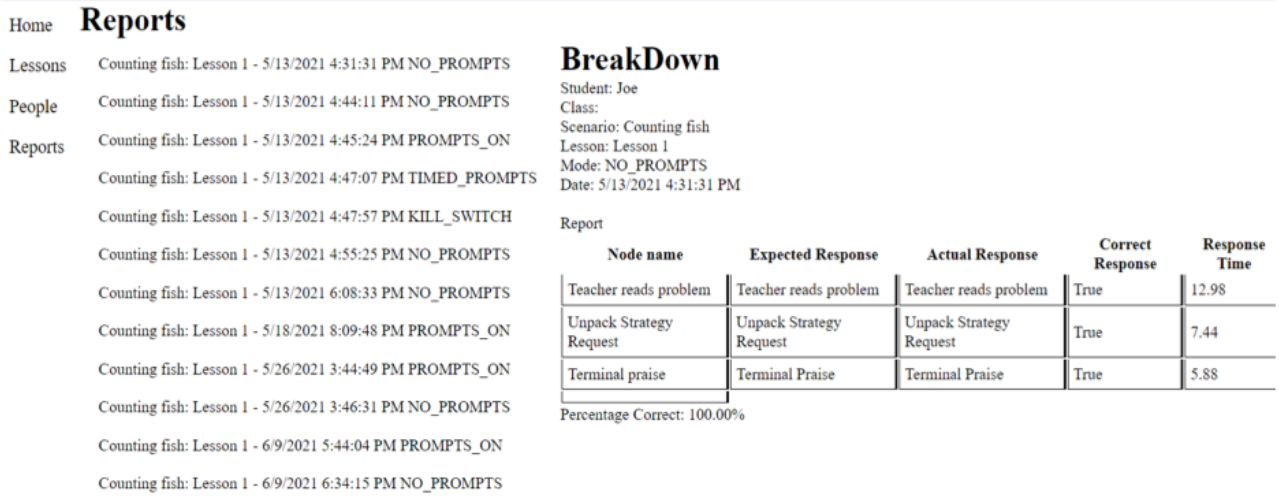

Figure 4. Depiction of basic virtual scenario and textual user prompt.

Procedures

Baseline

During the baseline session, the participants completed a brief demographic probe and the SKIL Survey. To acclimate the participants to VR, the participants completed a brief custom tutorial introducing them to concepts such as the need to depress and hold the right trigger while speaking as well as the appearance of onscreen prompts. The participants then completed 2 OMPs related to lessons 1 (ie, student avatar responds correctly) and 2 (ie, student avatar responds incorrectly). For both lessons, the initial prompt presented on the Oculus display—a math problem based on content commonly featured in 3rd grade mathematics—was "You have 5 fish bowls. There are 4 fish in each bowl. How many fish do you have total?" Together, the 2 OMPs evaluated the participants' ability to follow best practice over 10 teacher responses. The OMP for each lesson terminated immediately following an incorrect response. Although the system classified and scored each participant, the session administrator performed classifications manually to ensure an accurate assessment of the performance of the participants. Regardless of when the OMP was terminated, the simulation displayed "This concludes the session" at the conclusion of the probe. No further feedback was provided.

Training and Posttest Session

Overview

After the completion of the baseline assessments, the participants were randomly assigned to the control and experimental groups.

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Before assignment, we divided the entire sample into groups based on baseline OMP scores; members of these groups were then randomly assigned to the treatment conditions to ensure roughly equivalent baseline OMP scores for the control (mean 22, SD 4.140) and treatment groups (mean 22.67, SD 4.577). Sessions were conducted 1 week following baseline.

Control

The participants in the control condition watched a video-recorded lecture concerning the rationale and steps of the procedures for lessons 1 and 2. The lectures also included video models displaying educators using the procedures in practice with elementary-aged students. The lecture concluded with a description of the problem used in the OMP (ie, "You have 5 fishbowls…") and a description of how the procedures would be applied to this specific problem. The duration of the lecture was approximately 12 minutes. Following the lecture, the participants completed the same OMP used during the baseline sessions. In addition, the participants completed a generalization OMP featuring a novel problem: "There are 4 buckets. There are 3 apples in each bucket. How many apples are there total?" The student avatar's responses were adjusted to accommodate the new prompt. The generalization OMP terminated following the first incorrect response.

Intervention

The participants in the intervention group observed the same recorded lecture provided in the control condition. Thereafter, the participants received a series of supplemental VR trainings. For each lesson, the participants received 2 simulations of error-free prompting (EFPT), followed by 2 sessions of delayed prompting (DPT). EFPT simulations followed the general format of typical OMP; however, written examples of correct responses appeared on the screen immediately after each statement made by the student avatar. For DPT, prompts appeared on the screen following an incorrect response or nonresponse (ie, no response within 4 seconds). Immediately following each DPT, the simulation displayed the percentage of steps completed correctly and a description of the steps of each procedure missed (ie, performance feedback [48]). Classifications of participant performance, prompts, and feedback were all managed by the simulation without input from the session administrator. The combined duration of the supplemental VR trainings was approximately 10 minutes. The participants completed both the acquisition and generalization OMPs following training.

Maintenance

One week following the posttest sessions, the participants from both groups completed an additional acquisition OMP and generalization OMP in accordance with the procedures observed in the baseline and posttest sessions. The participants also completed an additional SKIL Survey as well as an assessment related to the acceptability of the training.

Analysis

For OMPs, a 2-way mixed-design ANOVA was used. The analysis evaluated differences using a between-participants factor of treatment (control or intervention) and a within-participant factor of time (baseline, posttest, and maintenance sessions). Partial eta squared, η_p^2, was used to indicate the extent of group differences, with values of 0.02, 0.13, and 0.26 representing small, moderate, and large effects, respectively [49]. Statistically significant main effects, if observed, were followed by an analysis of simple effects using within- and independent samples *t* tests (2-tailed). Effect sizes were determined using Cohen *d*, with values of 0.8, 0.5, and 0.2 for large, medium, and small effects, respectively [50]. Sphericity, normality, and homogeneity were evaluated using Mauchly, Shapiro-Wilk, and Levene tests, respectively.

The differences between the SKIL Survey responses in the baseline and maintenance sessions were analyzed using the Mann-Whitney *U* test, a nonparametric alternative for comparing group differences [50]. Effect sizes were determined using Cohen *r*, with scores exceeding 0.5 representing a large effect, scores between 0.49 and 0.3 representing a moderate effect, and scores between 0.29 and 0.1 representing a small effect [51]. We initially examined differences in confidence, given that knowledge and usefulness ratings were likely to stem from didactic instruction (ie, information received by the participants rather than opportunities for practice), which did not differ between the 2 groups. In addition, the results of our previous research suggested that these 2 dimensions are insensitive to VR training [13]. However, we compared the findings across the knowledge and usefulness scales as an exploratory analysis.

Correspondence, defined as OMPs and VMP recording the same value (eg, correct or incorrect) for a participant's response, was collected for each acquisition assessment, generalization assessment, and the VR simulations comprising the supplemental instruction. The calculations involved dividing the number of correspondences by the total number of responses and multiplying by 100.

Multiple comparison corrections were conducted for the 15 a priori statistical tests and 4 additional post hoc tests using the Benjamini-Hochberg procedure [52] with a false-discovery rate of 10%. [52] with a false-discovery rate of 10%. All raw *P* values, reported throughout, were significant following the Benjamini-Hochberg procedure unless indicated otherwise. All analyses were conducted using SPSS (IBM Corp).

Interobserver Agreement

Interobserver agreement (IOA) was collected across all phases of the project. Specifically, a doctoral-level faculty member (ie, the secondary observer) with experience observing the completion of the mathematical questioning procedure [14] collected OMP data—including generalization probes—in 43% of the baseline sessions, 28% of the posttest sessions, and 20% of the maintenance sessions across treatment and control groups. The secondary observer's results were compared with those of the session administrator. IOA was then calculated by dividing the number of agreements (ie, steps in the procedure in which observers recorded the same response) by the total number of steps in lessons 1 and 2 and multiplying the resultant number by 100%. The average IOA for the baseline and posttest sessions was 100% (SD 0%). The average IOA for the maintenance session was 100% for the experimental group and 93.33% (SD 9%; range 80%-100%) for the control group.

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Fidelity

We assessed the experimental protocols across all conditions using the checklists featured in our previous work [14]. The checklists indicated whether the session administrator delivered appropriate instructions, assessments, and simulation components. Fidelity was collected across numerous sessions in the baseline (43%), posttest (26%), and maintenance conditions (20%) and determined by calculating the percentage of steps for each session performed by the session administrator. The average baseline fidelity was 98.07% (SD 4.69%; range 87.50%-100%). In the posttest sessions, fidelity for the control and experimental groups was 100% and 95% (SD 5.77%; range 90%-100%), respectively. Fidelity across maintenance sessions was 100%.

Acceptability

During the maintenance session, we used a consumer satisfaction survey featured in previous studies [13] to assess the acceptability of the simulation. The participants responded to statements concerning the project (ie, *The use of VR was acceptable to me; I had no difficulty using VR*) using a 6-item scale (1=*strongly disagree*; 6=*strongly agree*). The participants also answered a series of questions related to their experiences in the simulation.

Results

Overview

Descriptive statistics for baseline, posttest, and maintenance variables are listed in Table 3.

Table 3. Descriptive statistics for baseline, posttest, and maintenance variables across groups.

Variable	Total	Control	Intervention
Pretest session			
OMP[a] (percentage of correct responses), mean (SD); range	22.33 (4.30); 20-30	22 (4.14); 20-30	22.67 (4.58); 20-30
SKIL variables			
Knowledge, mean (SD); range	1.28 (0.47); 0.50-2.25	1.48 (0.49); 0.63-2.25	1.08 (0.37); 0.38-1.63
Confidence, mean (SD); range	1.19 (0.61); 0-2.13	1.42 (0.60); 0.13-2.25	0.97 (0.54); 0-1.63
Usefulness, mean (SD); range	1.73 (0.60); 0.38-2.75	1.83 (0.60); 0.38-2.5	1.63 (0.61); 0.5-2.75
Posttest session			
OMP			
Percentage of correct responses (% correct), mean (SD); range	75.67 (22.08); 40-100	63.33 (22.64); 50-100	88.00 (22.62); 40-100
Generalization, percentage of correct responses, mean (SD); range	76.33 (24.70); 30-100	66.00 (22.62); 30-100	86.67 (22.89); 50-100
SKIL variables[b]			
Knowledge, mean (SD); range	2.36 (0.52); 1.25-3	2.27 (0.53); 1.25-2.88	2.45 (0.51); 1.5-3
Confidence, mean (SD); range	2.23 (0.51); 1.38-2.88	2.04 (0.52); 1.25-2.75	2.41 (0.45); 1.5-2.88
Usefulness, mean (SD); range	2.70 (0.32); 1.88-3	2.68 (0.35); 1.88-3	2.72 (0.30); 2-3
Maintenance session			
OMP			
Percentage of correct responses, mean (SD); range	69 (24.96); 30-100	54.67 (15.98); 30-100	83.33 (24.40); 50-100
Generalization, percentage of correct responses, mean (SD); range	72.33 (25.69); 30-100	58 (20.07); 30-100	86.67 (22.89); 50-100

[a]OMP: observed mastery probe.

[b]Knowledge, confidence, and usefulness were determined using 4-point scales from the SKIL Survey [36].

OMP Assessment

Acquisition

The Mauchly test indicated that the assumption of sphericity (ie, the equality of variance among difference scores among all testing variables) was not violated (χ^2_2=0.6; P=.74). A Shapiro-Wilk test indicated that the distribution of assessment scores for both groups across the baseline, posttest, and maintenance OMP assessments violated the assumption of normality (P≤.02). Nonetheless, we performed a mixed-design ANOVA, given that previous data simulations [53] suggested that ANOVA remains robust when data are not normally distributed. For the baseline and postintervention outcomes for the OMPs, a Levene test indicated that all the measures met the assumption of homogeneity. However, the results of the Levene test suggested that the maintenance scores violated the assumption of homogeneity (P=.04). Nonetheless, an ANOVA was performed, given that it is generally robust against violations of homogeneity when sample sizes are equal [54].

We analyzed the data using a mixed-design ANOVA with a between-participants factor of treatment (control and intervention) and within-participants factor of time (baseline, posttest, and maintenance sessions). Large main effects of time ($F_{2,27}$=124.154; P<.001; η_p^2=0.816) and treatment

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($F_{1,28}$=19.281; P<.001; η_p^2=0.408), as well as the interaction effect ($F_{2,28}$=8.429; P<.001; η_p^2=0.231) for the OMPs were significant, suggesting a difference in performance between the 2 groups at each time point. Subsequent simple effects tests of within- and between-subjects scores were performed to determine whether the 2 randomly equivalent groups differed.

Within-samples t tests revealed a large, significant improvement for the control group between the baseline and posttest sessions (t_{14}=−10.313; P<.001; Cohen d=2.66) and a significant decrease in performance between the posttest and maintenance sessions (t_{14}=2.303; P=.02; Cohen d=−0.595). Similarly, the intervention group exhibited a large, significant improvement in performance between the baseline and posttest sessions (t_{14}=−11.859; P<.001; Cohen d=3.062); however, differences between the posttest and maintenance sessions were not significant (t_{14}=0.699; P=.20), reflecting more stable performance across the 2 probes.

We also performed independent samples t tests comparing the performance of the control and intervention groups at each time point. Differences in baseline acquisition OMP were not significant (t_{28}=0.418; P=.40). However, differences between the intervention and control groups were both large and significant at the posttest (t_{28}=3.653; P<.001; Cohen d=1.334) and maintenance sessions (t_{28}=3.807; P<.001; Cohen d=1.39), suggesting that the VR simulation increased scores relative to the participants who exclusively received the lecture.

Generalization

Within-samples t tests on the generalization OMP revealed a moderate, significant decrease between the posttest and maintenance probes for the control group (t_{14}=1.824; P=.045; Cohen d=−0.471). Changes between the posttest and maintenance sessions for the intervention group were not significant (t_{14}=0; P=.50). Independent samples t tests revealed robust, significantly higher scores for the intervention group at both the posttest (t_{28}=2.488; P=.01; Cohen d=0.908) and maintenance sessions (t_{28}=3.647; P<.001; Cohen d=1.332).

SKIL Survey

The participants ranked their knowledge, confidence, and understanding of 8 criteria pertaining to the questioning procedure during the baseline and maintenance sessions using the SKIL Survey. We averaged the 8 dimensions of each value across each domain (Table 3). The treatment group reported lower ratings across all scales, relative to the control group, before the intervention. Following the intervention, the ratings across all scales were higher for the treatment group. Statistical comparisons of ratings at baseline and maintenance, performed using the Mann-Whitney U test, were initially limited to the confidence domain. The control group exhibited small, significantly higher confidence ratings than the intervention group at baseline, with U=64, P=.04, and Cohen r=0.142. At maintenance, the intervention group exhibited small, significantly higher scores than the control group, U=64, P=.04, Cohen r=0.137. However, inclusion of the knowledge and usefulness scales in the statistical analyses resulted in insignificant adjusted P values across all scales, including confidence. Following the Benjamini-Hochberg procedure, we observed no significant differences between knowledge and usefulness either before (U=57, P=.02 and U=83, P=.22) or after the intervention (U=85, P=.25 and U=107, P=.82).

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Across all conditions and groups, the average correspondence between the acquisition OMP and VMP was 95.98% (SD 7.44%; range 71.43%-100%). The correspondence between generalization OMP and VMP was slightly lower (mean 92.44%, SD 10.30%; range 66.67%-100%). Although not included as measures of performance, we also collected observation data during the probes conducted as part of the intervention (ie, EFPT and DPT). The correspondence between the observed and automated measures during the intervention was high (mean 98.03%, SD 2.96%; range 90.48%-100%).

Acceptability

Both the treatment (mean 5.73, SD 0.59; range 4-6) and control (mean 5.65, SD 0.82; range 4-6) groups provided high acceptability ratings for the VR portions of their conditions. The treatment (mean 6) and control (mean 5.87, SD 0.35; range 5-6) groups likewise agreed that they had no difficulty using VR.

Discussion

Principal Findings

This study compared the effectiveness of a training package featuring VR with didactic instruction as a means of teaching steps in a mathematical questioning strategy. Although participant performance improved following both forms of instruction, the results suggest that gains of the control group deteriorated during maintenance. Differences in performance between the posttest and maintenance sessions favored the VR group, whose scores were significantly higher than those of the participants who received didactic instruction exclusively. A similar pattern of performance was observed for untaught generalization measures. Notwithstanding the results of exploratory analyses featuring all the SKIL Survey scales, the results further suggest that VR contributed to higher confidence in the performance of the procedure. The correspondence between the measures of performance administered by human observers and those administered by AI was generally high. These positive findings, combined with favorable acceptability ratings, support broader applications of VR in education and provide avenues for future inquiry.

Differences observed between the treatment and control groups, although consistent with the positive effects observed in recent literature involving education and VR, were more pronounced in this study than in many previous studies [17,55]. This is likely because of the relatively low responses of participants in the baseline OMP, which mitigated the ceiling effects imposed by the primary measure. In addition, our VR training adapted an evidence-based approach to personnel preparation [29]. Although many simulations are premised on the belief that engagement in a simulated activity with little immediate guidance is beneficial to the learner [56], the findings from this study provide further support for immediate feedback associated

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with behavioral teaching methods and facilitated through automation [57]. Likewise, the high acceptability of VR across groups corresponds with the growing body of research [50] suggesting that modern VR hardware and approaches to simulation have alleviated motion sickness and other issues associated with earlier VR applications in education [15].

Given that the participants in previous studies required days of exposure to the simulation before mastering the procedure [14], the extent to which the treatment group participants acquired the procedure following a single session was surprising. The findings further suggest that the participants in the control group scored significantly lower on maintenance assessments, whereas scores in the intervention group did not significantly deteriorate. These results must be placed in the context of the limited number of items included in this experiment; nonetheless, the finding that simulation facilitated individualized skill rehearsal—often difficult to arrange in instructor-administered professional development and teacher education programs—provides substantial support for the use of automated opportunities for rehearsal as a supplement to typical instruction. Similar results in the generalization OMP likewise provide qualified support for the VR condition and support the contention that the participants were not merely memorizing appropriate responses based on the original problem. Nonetheless, future work will need to demonstrate the effect of the intervention on a wider range of problems and in practice.

Comparisons between OMPs and VMP revealed acceptable levels of agreement across the conditions. However, the disparities across conditions (ie, higher correspondence in prompting conditions relative to assessments) suggest that the feasibility of AI assessment in professional development, in the absence of extensive classification training, should vary based on the objectives of instruction. That is, the classifier used in this study appears to be suitable for procedures that require minimal deviation from a structured protocol or for determining the extent to which trainees exhibit statements closely aligned with training. As most trainings typically do not extensively assess individuals before instruction (ie, during baseline) and are designed to encourage the exhibition of targeted skills, the capabilities of the current automated system may be appropriate for the typical training context.

Limitations

This study has several notable limitations. The small convenience sample comprised students from a number of backgrounds that differed considerably from many professionals in education. Therefore, the results may not resemble those likely to be achieved among the targeted population. Given our research questions and the early stage of this scholarship, our emphasis on functionality, rather than external validity, is nonetheless appropriate. In addition, the VR group received more exposure to the procedure than the control group, whose participants did not receive a conventional alternative to the rehearsal provided in VR. However, the more passive training provided to the control group is representative of the instruction that appears in many preservice programs [1] and in-service professional development trainings [2]. The comparison in this study is appropriate because the primary purpose of AI-enhanced VR is to provide opportunities for rehearsal in instructional situations where individualized role-play is not possible. Given the emphasis on speech, we could have implemented the active components of the training using a less immersive platform (eg, a desktop computer). Nonetheless, the current integration of VR and AI contributes to the literature, given (1) the common view that immersion alone provides a benefit to the learner [38] and (2) the limited work regarding the use of AI and VR in teacher training [22]. Additional research is needed to compare immersive simulations with more conventional training approaches and explore the impact of emerging technologies on teacher education and professional development.

Future Directions

The current VR simulation demonstrates the feasibility of providing instruction in teaching methods using an automated version of an evidence-based training method (ie, BST). Additional work is needed to demonstrate positive effects across a broader range of procedures and settings. The current system analyzes the user based on speech input, which is valuable given the heavy emphasis placed on verbal communication in education. However, the opportunities VR provides to analyze head movement, controller positions, and gaze are what separate the technology from more common platforms. VR training provides opportunities to rehearse behaviors used in practice [58,59] rather than button pressing or other distal representations of authentic performance [13]. Incorporating motion sensing and speech recognition into future work can provide opportunities to train a wide range of complex skills.

Demonstrating the ability of VR-based instruction to promote generalization beyond simulated environments to authentic settings remains a fundamental challenge for the medium [58]. Behavioral theories of learning suggest that prompts and reinforcers can be paired with a variety of antecedents (ie, multiple exemplars) to create antecedent stimulus classes that should nonetheless produce the same response from the learner [39]. This has implications for VR instruction, as learners must (1) be capable of generalizing skills learned in simulations to the actual performance context and (2) apply targeted skills when confronted with situations that do not precisely resemble the situations addressed in training. The ability of VR to alter aspects of a learning simulation across repeated uses (eg, avatar behavior and appearance) has the potential to assist practitioners in generalizing their skills [7]. Randomizing student avatar characteristics (eg, gender and race) may also prevent the bias associated with repeatedly pairing specific types of student behavior with a specific student profile [59]. Addressing such issues will require research that stretches beyond the skills and application contexts featured in this study.

Conclusions

The findings of this study suggest that an automated, structured approach to VR can improve the acquisition of an educational procedure and participant confidence relative to more conventional, didactic methods. The participants further reported that VR was acceptable and easy to use. Automated assessments of performance generally corresponded to observations conducted by researchers, particularly in conditions where the probes were preceded by guidance regarding appropriate

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responses. Although promising, additional work is required to explore the effects of AI-enhanced VR on more complex procedures and the cascading effect of such training on practitioners in the field.

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Conflicts of Interest

None declared.

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Abbreviations

AI: artificial intelligence
BST: behavioral skills training
DPT: delayed prompting
EFPT: error-free prompting
IOA: interobserver agreement
OMP: observed mastery probe
VMP: virtual mastery probe
VR: virtual reality

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Original Paper

Integrating a Video Game Recording Into a Qualitative Research Methods Course to Overcome COVID-19 Barriers to Teaching: Qualitative Analysis

Nichole Stetten[1], MPH, PhD; Kelsea LeBeau[2], MPH, PhD; Lindsey King[3], MPH, PhD; Jamie Pomeranz[1], PhD

[1]Department of Occupational Therapy, University of Florida, Gainesville, FL, United States

[2]Veterans Rural Health Resource Center, North Florida/South Georgia Veterans Health System, Gainesville, FL, United States

[3]Department of Health Services Research, Management & Policy, University of Florida, Gainesville, FL, United States

Corresponding Author:
Nichole Stetten, MPH, PhD
Department of Occupational Therapy
University of Florida
1225 Center Drive
PO Box 100164
Gainesville, FL, 32610
United States
Phone: 1 3522739789
Email: n.e.stetten@phhp.ufl.edu

Abstract

Background: Because of the COVID-19 pandemic, a doctoral-level public health qualitative research methods course was moved to a web-based format. One module originally required students to conduct in-person observations within the community, but the curriculum was adapted using a web-based video game exercise.

Objective: This study sought to evaluate students' perceptions of this adaptation and determine whether the new pilot format successfully met the module's original learning objectives.

Methods: Recorded footage of a video game session was used for students to observe, take field notes, and compare the results. Qualitative methods were used to evaluate student feedback on the curriculum and determine whether the original learning objectives were met. Data were analyzed using a directed content analysis.

Results: The findings demonstrate that all the learning objectives of this adapted qualitative observational research assignment using a web-based video game exercise were successfully met; namely, the students learned how to compare and contrast the observational notes of peers and to evaluate how personal bias and environmental factors can affect qualitative data collection. The assignment was also positively received by the students.

Conclusions: The results align with the constructivist learning theory and other successful COVID-19 implementations. Our study demonstrates that the learning objectives of a qualitative observational assignment can be addressed given that there are proper forethought and delivery when the assignment is adapted to a web-based context using a video game exercise.

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KEYWORDS

qualitative research; pedagogy; COVID-19; video games; educational technology; web-based learning

Introduction

Background

On March 11, 2020, because of the COVID-19 pandemic, the University of Florida (UF) temporarily adapted all in-person courses to a web-based format. By mid-March, all classes were permanently moved to the web for the remainder of the spring semester and continued to be held this way throughout the summer semester. Courses traditionally held in person were mandated to quickly adapt to a web-based format. A brief COVID-19 timeline for UF is presented in Figure 1.

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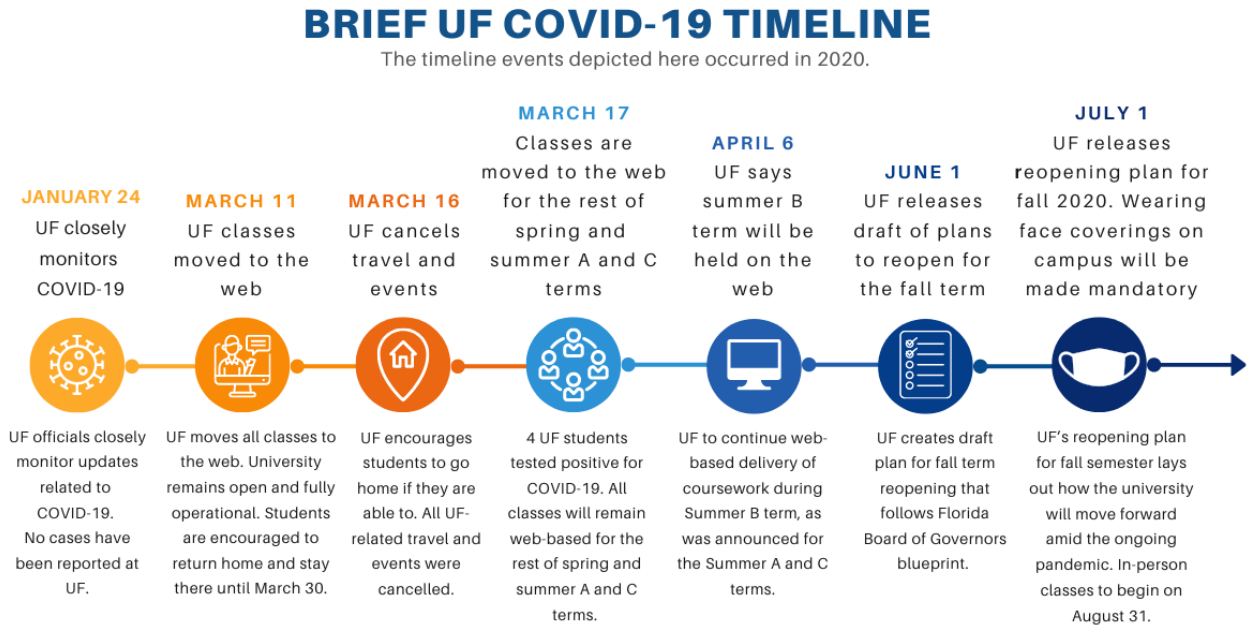
Figure 1. Brief University of Florida COVID-19 timeline. FL: Florida; UF: University of Florida.



Teaching Qualitative Research Methods on the Web

Good observation, interviewing, and communication skills are crucial for producing high-quality data for qualitative research that are reliable, trustworthy, and rigorous. These skills require a great amount of interpersonal ingenuity and are best modeled to students through in-person synchronous courses [1,2]. As colleges and universities strive to become more accessible, many courses have evolved to be taught on the web using an asynchronous format, in addition to the traditional in-person courses [1-4]. Approximately 28% of students undergoing higher education take at least one web-based learning course [5].

Teaching practices in web-based qualitative research methods have become an important topic of inquiry as opportunities for web-based and distance education increase [4]. Despite the shift to providing master's- and doctoral-level courses on the web, there is little guidance on how to adapt qualitative research methods courses to web-based, distant formats of learning [4,6]. Specifically, there is an underdeveloped knowledge base surrounding web-based qualitative education, and existing instructions mostly emphasize face-to-face approaches [4].

Qualitative Pedagogy and Curriculum Development

There is currently minimal direction regarding the adaptation of qualitative courses to web-based formats despite qualitative research methods comprising a core part of the curriculum for doctoral programs [6]. However, over the last few years, qualitative educators and researchers have begun building these foundations through innovative pedagogical approaches and curriculum development. Qualitative educators have applied different types of instructional strategies in web-based qualitative courses with varying degrees of success (ie, instructional media, web-based discussions, applied research activities, and writing projects) [4].

Innovative curriculums have been created using pedagogical models designed to better incorporate technology and media into the classroom, such as the ASSURE (Assure Learners, State Standards & Objectives, Select Strategies, Technology, Media & Materials, Utilize Technology, Media & Materials, Require Learner Participation, and Evaluate & Revise) model and Four Component Instructional Design model [7,8]. Additionally, 3D web-based environments have been successfully used to teach students ethnographic qualitative research methods in the web-based world of *Second Life*, in turn providing a student-centered approach to teaching and learning [3,7-11]. Furthermore, *World of Warcraft*, a massively multiplayer online role-playing game with a 3D web-based world, was used to teach a web-based doctoral level research methods course using a duoethnographic approach [6].

Developing web-based qualitative courses focuses on maintaining the same rigorous approaches and strategies as those followed in traditional in-person courses [4,10]. Commonalities among web-based courses have shown that the successful conversion of an in-person qualitative research methods course into a web-based one requires significant time and a diverse team of experts. Experts should not only be from the qualitative research field but also from the fields of instructional design and distance learning. Furthermore, adoption and diffusion of web-based qualitative research methods courses require technology innovators and early adopters [3,8,10,12]. Unfortunately, the COVID-19 pandemic has caused courses to be rapidly adapted to web-based formats, severely limiting the resources, time, and diverse professional expertise needed for teaching qualitative research methods on the web.

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Video Games and Instructional Videos as Pedagogical Tools

Researchers have shown that video games can facilitate significant learning and can be a useful pedagogical tool for instructors and educators in various academic settings [13,14], including video games designed for educational purposes (serious games) and commercial video games designed for fun and entertainment. In higher education settings, the combination of educational content and video games has been implemented to "increase student engagement" and "help achieve learning outcomes" [14]. This has been accomplished through serious games, traditional computer games, mobile games, and the modification or adaptation of commercial video games [14]. Video games in higher education have been applied to the fields of science [14,15], nursing [7,11,16], and health care leadership [9], with less application in other fields such as qualitative research and research methods.

In other research settings, instructional videos for teaching in higher education have also been shown to be an effective content delivery and pedagogical tool and cost-effective [17-20]. Instructional videos can help reimagine learning by presenting content in new ways yet offering engaging and high-value learning experiences in a web-based environment. They can also improve student learning and engagement, such as by allowing students to review or rewatch content from video recordings [17,20]. There are mixed findings regarding instructional videos because they do not always allow students to engage with the materials in the videos [21]. Creative strategies could be used to circumvent this by facilitating more active learning, such as using a video game recording where the student is following along with the video game player, figuring things out as they go, and integrating and applying the course content [17,19,21]. It is reasonable to assume that this success could be extended to video game recordings. However, knowledge regarding the use of video game recordings in higher education is lacking.

Modifying or adapting video games for educational purposes is a more recent phenomenon in the educational setting, one that continues to gain traction given that it is less expensive and resource intensive and provides instructors with a game environment that can be controlled and modified to fit the course and learning needs to students. It is important to expand the knowledge base of instructional technologies as pedagogical tools in higher education, including the modification or adaptation of video games such as video game recordings. This is especially valuable for fields that have not garnered much research attention but are central to many curriculums.

Objectives

This study does not examine a qualitative research methods course in its entirety, as it was not developed for web-based learning. Instead, our pilot study examines how a traditional qualitative assignment that could have been assigned in person or on the web but would have been impossible to complete in person due to the COVID-19 pandemic. After considering the COVID-19 pandemic–related constraints, a web-based version of the assignment was developed using a recorded video gaming session to cultivate the competencies that the students would have acquired had the assignment been in person. The objectives of this study were to explore whether the pilot adaptation successfully met the learning objectives of the module and to explore students' perceptions of the adapted assignment. Perceptions have been operationally defined as the students' understandings and interpretations of the COVID-19–adapted assignment. Overall, this study hopes to add to the body of literature to support other instructors in adapting their qualitative courses to a web-based format.

Research Questions

This study aimed to answer two research questions: (1) How were the learning objectives met after the assignment was adapted during the COVID-19 pandemic? and (2) What were the students' perceptions of the assignment?

Methods

Study Design

Data were collected from a doctoral-level qualitative research methods course that included social and behavioral science public health students and rehabilitation science students. Due to the course being an upper-level doctoral course, student registration was limited to allow for deep discussions and engagements. A total of 7 students were enrolled in the study. Data were collected from an observational research assignment and students' overall course feedback. Qualitative methods were used to evaluate students' (N=7) course feedback and determine whether the learning objectives were met. Data were analyzed using a directed content analysis [22]. Figure 2 shows a diagram of our research process and methodological decision-making. A video game recording, an instructional technology, was selected as a pedagogical tool to deliver content and facilitate high-level learning within the web-based qualitative research methods course. The video game recording was leveraged as a learning tool to meet the educational needs of students during the pandemic while also attempting to meet the learning objectives of the qualitative research methods course. In alignment with game-based learning research [22], the goal was to create a recorded game environment that could be effectively used to develop subject-specific skills (eg, observational skills), replacing an in-person experience.

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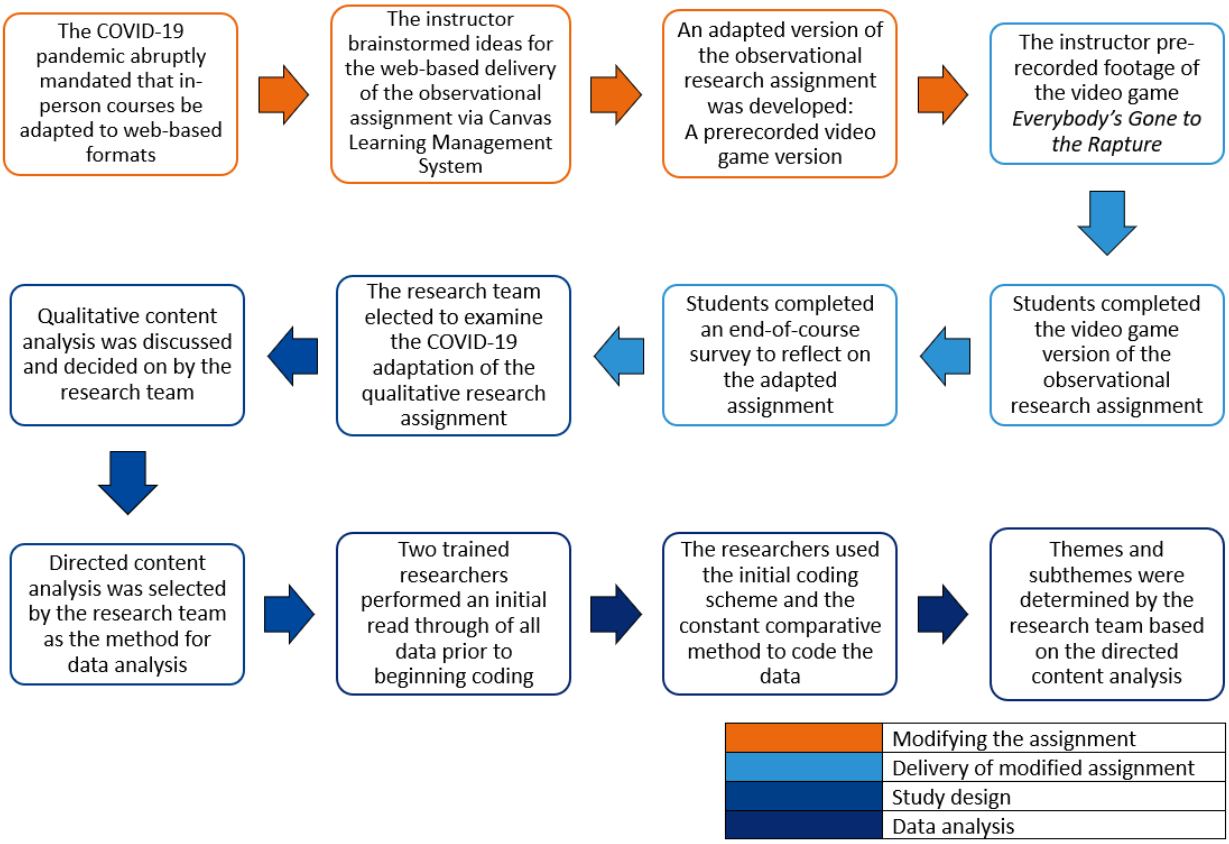
Figure 2. The research process and methodological decision-making.



Ethics Approval

We obtained institutional review board (IRB) approval from the UF IRB (IRB202002357). Students completed course evaluations and an evaluation of this assignment while they were enrolled in the course, and there was no research intent to use the data. Once the course was completed, the instructor applied for IRB approval to use feedback in these evaluations. Our study was approved as exempt, and informed consent was not required.

Directed Content Analysis

A content analysis was chosen, as we sought to "provide knowledge and understanding of the phenomenon under study" [22]. A directed content analysis is used when there is prior knowledge, research, theory, or concepts that directly provide coding categories. A directed content analysis specifically follows a deductive qualitative approach, as it aims to test a specific set of learning objectives. For example, because assignments are specifically created to meet a module's learning objectives as part of the standard curriculum development, these objectives would ultimately appear in our analysis, thus providing the initial coding categories. The initial analysis coded the text using these initial coding categories (ie, 3 learning objectives), and content that did not fit the original coding scheme was assigned a new code.

Qualitative Trustworthiness

Quantitative research measures such as reliability and validity are not used for qualitative studies. Rather, qualitative research relies on the concept of "trustworthiness" instead of reliability and validity [24,25]. The tenets of trustworthiness are credibility, transferability, dependability, and confirmability. In this study, credibility and confirmability were used to prevent bias and improve trustworthiness. In the next section, we elaborate on how we used triangulation. To improve confirmability, 2 researchers independently analyzed the data using predetermined themes, as described in the data analysis section [24,25].

Triangulation

Triangulation is the use of "multiple methods or data sources in qualitative research to develop a comprehensive understanding of a phenomena" [26]. Of the 5 triangulation types (ie, data, investigator, theory, methodological, and environmental), data and investigator triangulations were used. Data triangulation involves the use of different sources of data in the analysis [26]. This was accomplished by analyzing students' answers to the assignment and course feedback (which did not directly ask students about the adapted assignment). Despite not being directly asked about the adapted assignment, most students discussed it in their course feedback. Investigator triangulation involves the use of different investigators to conduct data analysis [26]. The researchers first analyzed the data independently before coming together to compare the results. To prevent bias, the course instructor did not analyze the data. Instead, 2 researchers who were not involved in the course or assignment analyzed the data (establishing confirmability).

Pre–COVID-19 Pandemic Assignment

During the traditional, face-to-face qualitative research methods course, students learned about different qualitative research

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techniques (eg, observation, interviews, and focus groups). Observation research is a qualitative technique in which researchers observe and record participants' ongoing behavior in a natural situation. A central method used in observation research is creating observational field notes, which are descriptive, reflective, and evaluative information documented by the researcher to record observations [27]. A weakness of observational research is bias, as researchers can observe things or interpret observations differently as a result of their personal biases [27]. When teaching qualitative research, students are encouraged to practice reflexivity, wherein they reflect on and identify how their personal biases could affect data collection and analysis.

In the pre–COVID-19 pandemic assignment, to teach students about observational research and personal bias, they were asked to pair up with another student, go out into the community, and observe humans in their natural environment for a fixed period, for example, going to a coffee shop and observing the patrons in the coffee shop or focusing on a specific subset of people in that coffee shop (ie, a couple on a date, a mother and child, etc). Students were asked to observe and record observations separately and then pair up to compare the field notes.

COVID-19 Pandemic–Adapted Assignment

Due to the COVID-19 pandemic and state restrictions, the face-to-face assignment described above was impossible to complete and needed to be adapted to the current circumstances (Figure 2). To provide an observational research experience, the instructor innovated a curriculum using a recorded video game session as a medium for the delivery and mastery of content. The instructor recorded footage of their avatar playing the video game *Everybody's Gone to the Rapture* (Sony Computer Entertainment America LLC). In *Everybody's Gone to the Rapture*, the player explores a small English town whose inhabitants have mysteriously disappeared. The objective of the game is to explore and discover how and why everyone has disappeared. While playing the game, the player follows around a mysterious orb of light that leads them to a scene depicting an event or interaction among the town's occupants. These scenes, as well as other environmental cues (tape recordings, radio broadcasts, and items left by previous inhabitants), allow the player to surmise what happened. After recording 4 hours of footage, the instructor edited the video to be 30 minutes long. The 30-minute recorded video game session served as the observation environment for the students, replacing the need for in-person observations during the pandemic.

This game was chosen for the adapted assignment because it encourages exploration and careful observation. Furthermore, the game environment allowed the instructor to create highly controlled and modifiable content for the course that mirrored the face-to-face assignment in several ways. First, the observations made while watching the prerecorded footage were similar to the observations students would make while in a coffee shop. Second, both assignments required students to take observational field notes of their respective settings. To elicit similar observational experiences among the students, they were instructed to view and take observation notes on the video recording without pausing the video. This instruction was given to illicit what a live or real-time observation would feel like while taking observation notes. Finally, both assignments involved students using environmental clues and dialogue to note what they observed. The instructor had familiarity with *Everybody's Gone to the Rapture*, which was a contributing factor to its choice for the adapted assignment. The instructor's prior experience with the video game made it possible to knowledgeably align curriculum development and instructional goals with the game attributes, which has been recommended in educational gaming literature [6].

The students were separated into groups of 2 or 3 and asked to observe the main character in the story and how they interacted with the world while taking field notes. The students were instructed to watch the video on their own and answer several questions about what they thought was happening in it. After doing this, the students met with their partners on the web and were asked to compare their approaches to observation and taking field notes and understand how their accounts overlapped and varied. After working with their partners, they were asked to reflect on how their personal biases and current events affected their perceptions of the events in the video. The course assignment is provided in Multimedia Appendix 1.

Student Course Feedback

At the end of the semester, the students were asked to complete an end-of-course open-ended survey and reflect on which assignment, discussion, or activity they enjoyed the most and discuss why they felt that way. The students were also asked to reflect on the aspects of the course they did not enjoy and discuss why they felt that way. This end-of-course survey was similar to the one used in another study that investigated approaches to teaching web-based qualitative research methods [10]. This open-ended survey was designed to ask students more specific questions than what was asked of them on the university evaluation system. The instructor wanted to obtain this additional feedback to learn which assignments needed to be revised or removed for future classes and which assignments should remain in the course. Data from the course feedback were included in the analysis, as 43% (n=3) of the students mentioned the COVID-19 pandemic–adapted observational assignment in their feedback.

Data Analysis

A directed content analysis was used to investigate whether the modified assignment met the predetermined learning objectives and to understand students' perceptions of the assignment. Directed content analysis is 1 of the 3 approaches used in qualitative content analysis and is used when the study's frame provides initial coding categories for the study [23,28,29]. The initial coding scheme is displayed in Textbox 1 and consists of the learning objectives of the assignment. During the analysis, the data were coded by 2 trained researchers using the predetermined themes (ie, learning objectives). Data that could not be coded into the predetermined themes were analyzed and placed under new themes or subthemes. To ensure triangulation of the data, the constant comparative method [30,31] was used when organizing the data into the predetermined themes.

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Textbox 1. The initial coding scheme used for the directed content analysis.

Themes

- Learning objective 1: compare and contrast the observational field notes of peers who observed similar or the same phenomena.
- Learning objective 2: evaluate how personal bias can affect qualitative data collection.
- Learning objective 3: evaluate how environmental factors can affect qualitative data collection.

Results

Overview

Our directed content analysis resulted in 3 major themes directly related to the learning objectives. Subthemes were also identified during the analysis. The themes and subthemes are listed in Table 1. Students' names and pronouns were removed from the quotes to ensure confidentiality and limit identification. Students' names were changed to students 1, 2, 3, etc. Gendered pronouns were replaced with gender-neutral pronouns. The name Jeremy, which is used frequently by the students, is a name used in the video game recording and is not the name of a student or the instructor.

Table 1. Themes and subthemes from the directed content analysis.

Initial themes	Frequency, n
Learning objective 1: compare and contrast the observational field notes of peers who observed similar or the same phenomena	26
Subtheme 1.1: the web-based observational experience[a]	13
Learning objective 2: evaluate how personal bias can affect qualitative data collection	20
Subtheme 2.1: understanding one's role in the research process[b]	6
Learning objective 3: evaluate how environmental factors can affect qualitative data collection	16

[a]Operational definition: interpretation and feedback from the students after the completion of the observational experience.

[b]Operational definition: responses that helped the students identify their role as a researcher and challenged their assumptions as they worked through the observational research assignment.

Learning Objective 1: Compare and Contrast the Observational Field Notes of Peers Who Observed Similar or the Same Phenomena

There were 26 responses addressing learning objective 1. To accomplish this learning objective, the students observed the video game and documented field notes alone and then compared their field notes with those of a peer. After working in pairs, their observations were posted on the web on the designated e-learning discussion board, so they could compare their findings with those of other groups. By doing so, the students demonstrated an understanding of how people can observe and interpret a phenomenon in similar and different ways depending on various factors. For example, the excerpt below depicts how the perspectives of 2 students on environmental cues can overlap with one another yet also provide a new perspective, even when the assignment variables were held constant:

> *Accounts overlap in that we were very descriptive of environmental cues, car descriptions, etc. While another student was more narrative in [their] notes and was able to capture the audio conversations more than Student 1. Student 1 accounted more for situations surrounding the houses to account for the physical environment. Student 1 noted more subtle indications of location versus Student 6 noted final, solid indicators at the end.* [Students 1 and 6]

> *It is definitely interesting to see the different school of thoughts on exposure to the same video. Just as Student 1, I could only take short bullet point notes at a time and did not elaborate as much when typing. It is also interesting that Student 6 associated the event with rapture as I also had that as a possibility of what happened in the town.* [Student 4]

Students also discussed their enjoyment of the observation activity and the benefits of such an activity in a qualitative course. They emphasized the importance of recognizing that people can interpret similar events or situations in various ways:

> *I also enjoyed this activity as it was beneficial to understand how others interpreted the same video. The discussion solidified the differences between groups and individuals. Lastly, it reinforced the value of a team-based approach and having mechanisms in place to record your data to increase rigor.* [Student 6]

> *Student 2 and I were paired up for the observational fieldnotes assignment, which I enjoyed because it was this common stimulus and we got to experience how two researchers might approach the same dataset with different takeaways, each influenced by our experiences and biases.* [Student 5]

This recognition is important for qualitative researchers to ensure reliability and rigor throughout the qualitative process. Furthermore, the students discussed how the exercise of systematically comparing and contrasting their notes with those of a peer was helpful and broadened their perspectives on qualitative observational research:

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> *We thought about participating in research on a team; even for this simple project, it was helpful to talk about what we each interpreted from the scene as that led to richer ideas and discussions. Observational notes are unlikely to be reasonably separated from the perspectives of the observer; thus, the recursive process of qualitative can help here as you can refine your ideas over time with perspectives from other researchers and from the literature.* [Students 2 and 5]

Overall, the comments indicated that the students perceived collaborating with peers while completing the observational research as a valuable experience, which indicated that the learning objective of comparing and contrasting the field notes of peers who observed a similar phenomenon was met.

Subtheme 1.1: Web-Based Observational Experience

A subtheme emerged from learning objective 1 and was termed "web-based observation experience" (Table 1). This was operationalized as the interpretation and feedback from the students after the completion of the observation experience. Although this subtheme was related to the observation experience and the comparison of field notes among peers, it focused more on the comparison of the web-based observation experience with the real-world observation experience. Our analysis revealed 13 responses related to this subtheme:

> *If observing in real time, the observer may miss things when stopping to take notes; the perspective of making observations limits to what you can see, hear.* [Students 2 and 5]

The above comment could apply to a real-world observation or a web-based observation, whereas the following comments relate more to the ability to replay web-based observations multiple times:

> *The strategy that I used was pretty similar to yours. I tried to note the key points by jotting down notes in brief then going back later and putting them together in coherent statements. My strategy differed from yours because I treated the video as a recording that I could replay (I watched it twice and I used the pause command the second time through to allow time to jot down detailed notes like the time on the clock tower for example).* [Student 2]

> *Recording would be very helpful in research involving observations. This would give the opportunity to observe multiple times and not have to focus on taking detailed notes in the first viewing.* [Students 3, 4, and 7]

Both examples relate to how note-taking, whether performed while observing in person or on the web, may not allow a researcher to capture the full observation if the ability to record is not available. As student 4 stated, you "need more than one perspective present to compare and contrast what you observed." Overall, this demonstrated that students developed a deeper understanding of the strengths and limitations of observational research, especially those related to learning objective 1.

Learning Objective 2: Evaluate How Personal Bias Can Affect Qualitative Data Collection

The qualitative analysis of learning objective 2 yielded 20 responses related to personal bias affecting qualitative data collection (Table 1). The students discussed how their personal biases impacted their observations in ways that they were not aware of until they talked with their peers. For example, this student discussed how their public health background predominantly influenced their observations and interpretations, whereas their peer's observations and interpretations were heavily influenced by their religious beliefs:

> *I think my personal bias affected my observations in ways I did not know until my discussion with Student 6. They saw an element of religion and supernatural within the story, predominantly the role and symbolism of the orb. I am not a very religious individual, therefore, I relied on my public health background, which made me omit or neglect any signs of religion. I was only made aware of religion at all when scripture was recited to Jeremy [character in the game]. I think a very obvious bias was my assumption that he was a dad versus a religious leader. I think my background of science and rigor made it hard for me to be creative and open to a fictional situation, so I was trying to make connections within my reality, not the reality of the game.* [Student 1]

Several students also commented on their prior experience or lack of prior experience with video games and how that may have impacted the data collection:

> *I don't have much exposure to modern video games, so it's interesting to hear how experience with this type of "world" seems very helpful in navigating/interpreting a video like this. Coupled with Student 2's discussion of [their] electronics background and how it helped them interpret the video, I think this is a great illustration of how our own experiences and perceptions can influence our observations and interpretations.* [Student 7]

Many also commented on how their experiences with movies or books could have also influenced the data collection process:

> *I think horror movies, sci-fi movies (you mentioned you are reading a sci-fi book), and video games made me think aliens or something supernatural. One aspect that really connected me to aliens was actually the choir voices that were heard throughout [background music within the game]. In the video game "Halo," a similar ominous choir sound is heard, and it involves aliens. This exercise was a great example to demonstrate how our own personal bias can construe how we observe the world, for me, I think that went along with horror movies (specifically, zombie movies) where characters just need to survive in post-apocalyptic world. Exploring how your backgrounds/personal biases may have impacted how you viewed the video!* [Student 3]

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> *I realized my thoughts on what had happened were influenced by my love for sci-fi and horror series and movies. Similar events tend to be portrayed in such movies and I was quick to form theories or assumptions that were highly correlated with the content I had previously seen.* [Student 4]

The students demonstrated their ability to critically evaluate how personal biases, such as backgrounds and experiences, affected their qualitative data collection process. Based on their personal biases, the students processed how their approach to data collection varied and how this variation helped their overall comprehension of personal bias in research.

Subtheme 2.1: Understanding One's Role in the Research Process

The subtheme understanding one's role in the research process emerged from our analysis under learning objective 2. This subtheme was operationalized as responses that helped the students identify their role as a researcher and challenge their assumptions as they worked through the assignment (Table 1). A total of 6 student responses emerged.

Several students discussed how they struggled to determine what their role was within this assignment:

> *We made assumptions at the beginning that we eventually changed, which is seen throughout our notetaking. We struggled to identify who we were in this story, so we continually checked ourselves and our role. Are we part of the story or are we an external observer? We also realized the time-extensive nature of data collection and we only feel like we have a piece of the story. The notes left us with more questions than solutions, which may parallel how research questions are developed.* [Students 1 and 6]

Student 7 also discussed how they struggled to determine their role in the game:

> *Like Student 1 mentions, I initially assumed I was Jeremy [character in the game], once it became clear I wasn't Jeremy, I had the understanding that we are a first-person observer, as you describe. However, even as Jeremy I felt that I was trying to figure out what was happening/had happened in the village. While much of my interpretations of the light and its effect were similar to what you (Student 5) and Student 2 describe, it didn't occur to me that the light could also be functioning as a guide for the observer.* [Student 7]

Learning Objective 3: Evaluate How Environmental Factors Can Affect Qualitative Data Collection

For our third learning objective, the directed content analysis yielded 16 student responses. Based on their own experiences and other students' discussions of their respective experiences, the students contemplated whether certain environmental factors affected their data collection process and how this occurred during the observational assignment. Several students discussed how the COVID-19 pandemic directly or indirectly affected their perceptions of this assignment:

> *Seeing the quarantine signs immediately triggered a parallel to today's pandemic. My mind went to a virus outbreak and maintained that position through the entire narrative. I think this kept me from deviating to religious or supernatural explanations. Though the pandemic was subtlety influencing my perceptions, I think my personal biases and experiences were more dominant in influence. I was able to make connection such as closed businesses and required quarantines, but the differences in symptoms and apocalyptic state of the community was different enough for me to separate today's reality from the virtual one.* [Student 1]

> *I definitely think being in the middle of the COVID-19 pandemic impacted my perception of this video; I think this may have heightened my sensitivity to the term "quarantine" and its possible role in the events in the village, particularly in conjunction with the quarantine signs. I initially made the connection between the term quarantine and illness, and I assumed something had "infected" the individuals living in the village. This doesn't necessarily align with all of the other observations in this video…but it was consistently in the back of my mind while I watched the video and tried to piece together what might have happened.* [Student 7]

> *The ongoing pandemic made it easier for me to conclude that some form of infection spread through the town and led to people quarantining. The town had a number of quarantine signs posted on doors. It was easier to reach this conclusion after experiencing the implications of the emergence of COVID 19, unlike if I had not experienced this.* [Student 4]

Student 3 indicated an indirect effect of environmental factors on their data collection experience. At first, they did not think that the COVID-19 pandemic influenced their data collection. However, upon discussing and evaluating other students' responses to environmental factors, student 3 noted that they were "sensitive to the word 'quarantine'" throughout the assignment.

In addition to environmental factors affecting qualitative data collection experiences, the students also expressed that relevant environmental factors (ie, the COVID-19 pandemic) impacted their perceptions of the observational assignment:

> *I think that events surrounding COVID-19 affected the way I perceived what was going on in the video because I felt that the facilitators of this course would piggyback on current events to illustrate a point with regard to this module of instruction. It was a valuable experience in terms of recognizing subjective biases and controlling for them to enhance the likelihood of an objective exploratory exercise.* [Student 2]

Students exhibited their abilities to evaluate the influence their immediate environments might have on qualitative data collection. This was especially apparent when students discussed how the COVID-19 pandemic directly affected what they paid

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attention to in their web-based surroundings, which environmental cues most impacted their interpretations, and how they perceived what was happening through documented observational field notes.

Discussion

Principal Findings

Due to UF's mandated transition to web-based learning (Figure 1), it was necessary to create qualitative research assignments that could be implemented in a web-based environment. This study used learning objectives and student perceptions to examine the effectiveness of using a video game to replace a traditional in-person observational research assignment during the COVID-19 pandemic. The pilot COVID-19–adapted assignment successfully met all learning objectives. Although the learning objectives for in-person courses do not always readily conform to web-based contexts [32], our study demonstrates that learning objectives can be addressed given that there are proper forethought and delivery method. Even within the confines of rapidly adapting the observational assignment to a web-based context, our findings show that a web-based observational assignment can meet learning objectives.

Learning Objective 1

Our findings demonstrated that the students learned how to compare and contrast their observational notes with those of their peers who observed the same or similar phenomena through the video game assignment. Students were able to compare not only note-taking styles but also the level of detail recorded. As the students viewed the same prerecorded video game scenes, it was easy for them to identify how their observations were similar and how they differed. The students reported noticing key differences among observers and identifying the importance of comparing and contrasting field notes, showing that learning objective 1 was met through the web-based assignment.

This activity also reinforced the foundational concept of analyzing qualitative data using a team-based approach. This team-based approach begins to teach students the importance of triangulation in qualitative research, which helps ensure the validity of the results [26,33]. The students were provided first-hand experience with investigator triangulation, which occurs when ≥2 researchers observe a specific phenomenon. Multiple observations allow researchers to confirm and add breadth to findings through different perspectives.

The students' observations and notes were not just contained within pairs but also displayed on a discussion board so that the students could compare them among their classmates. This allowed the students to experience data source triangulation, which occurs when data are collected from different individuals with varying experiences and beliefs to gain multiple perspectives [26]. As the students were from different doctoral programs (rehabilitation science and social and behavioral science), they were trained to notice and see things from varying perspectives. In future courses, this can also be used to teach students additional factors that should be considered when conducting observational research (ie, ethics, consent, natural observation, laboratory or simulated observations, and equipment needed for recording).

Learning Objective 2

The findings also demonstrated that learning objective 2 was met through this assignment. Students learned to evaluate how personal biases can affect qualitative data collection. A core aspect of conducting qualitative research is reflexivity. Reflexivity is an awareness of the influence the researcher has on the environment and the people being studied as well as how the research affects the researcher [34,35]. A large portion of being reflexive is understanding how one's personal biases affect how one observes the world. After the students began to compare their findings with those of other students, they became aware of their biases and how their viewpoints were influenced by a particular lens. The students who had religious backgrounds noticed more religious symbolism than the students who were not religious. Some students with public health backgrounds interpreted events through more of a public health lens. Other students perceived events of the game as something supernatural—similar to a video game they had played, movie they had seen, or science fiction book they had read. The ability to identify one's biases and evaluate how those biases shape one's observations is important in any type of research, and it allowed the students to further understand the role they play in the research process. The students reporting their biases and reflecting on how their biases influenced their qualitative approach to the assignment demonstrated mastery of the skill identified through learning objective 2.

Learning Objective 3

There is plenty of research showing how environmental factors affect behaviors, but these factors can also impact data collection and analysis. *Everybody's Gone to the Rapture* displays signs of a quarantine as well as shows environmental cues that the residents were ill (tissues, blood, and dialogue between the residents about them being sick and worried). As the students were observing this within the game, in their real lives, they were surrounded by COVID-19. The students described how their minds made parallels to the ongoing COVID-19 pandemic, and them reflecting on how the world's current events influenced their perceptions, which showed that learning objective 3 was met.

Student Perceptions

At the end of the semester, the students mentioned this assignment as one of their favorite assignments for the course. Not only was it a change of pace for the students, but it also allowed them to work together on the web during a time of social isolation. During the prepandemic period, university students experienced high rates of depression and anxiety [36,37]. The COVID-19 pandemic and other world events (ie, wildfires, natural disasters, political unrest, etc) have caused a significant increase in depression and anxiety among students [38,39]. The students mentioned that they enjoyed working with other students via the web during the assignment. This highlights the importance of interactive assignments that allow students to connect with their peers when learning on the web [40] not

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only to reduce social isolation but also to create a sense of community within the classroom.

Theoretical Alignment, Qualitative Pedagogy, and Curriculum Building

Although the entirety of this study was not directly informed by the constructivist learning theory, our results suggest that the assignment aligns with the constructivist philosophy and teaching methodology of active learning through real-world experiences (ie, experiential learning) and student-centered approaches [9,11]. Constructivist environments and the associated approaches to learning allow students to obtain knowledge, master new skills, challenge assumptions, re-examine beliefs, and collaborate with classmates to make new connections and gain different perspectives [9,11,40]. Although the real-world setting was modified for a web-based learning environment, the thoughtful modification of our assignment allowed students to directly engage in active-learning experiences and times of reflection, and it encouraged the students to work through observational research processes as they completed the assignment.

Constructivist learning strategies also encourage multiple perspectives to represent the topic area of interest. The observation assignment had a discussion portion in addition to the video game portion. Franco and DeLuca [9] argued that group interactions and discussions are the elements required for success. The discussion required students to reflect upon their personal experiences observing the video game recording and present their reflections to their classmates to compare their experiences. Their classmates' approaches to observation techniques, as well as their own interpretations and understandings, were presented so that the students developed a well-rounded comprehension of observational research and field notes. In line with constructivism and experiential learning, this assignment provided the students with a self-directed learning environment and the opportunity to collaborate with their peers [9,11]. The assignment improves upon standard pedagogy by increasing student motivation and interaction through active-based learning and storytelling elements.

Comparison With Prior Work

Although the literature is limited because of the novelty of COVID-19 pandemic, our study and its findings align with the recently published literature concerning COVID-19 and teaching higher education [32,40-42]. With the implementation of our video game assignment, we intentionally adapted a traditional in-person assignment to reflect the activities students that would have experienced if the class were held in person. The assignment was adapted to provide students with a meaningful and interactive experience, which has been encouraged by researchers during the pandemic [32]. This study adds to the current COVID-19 literature by providing ideas, success stories, and lessons learned regarding adapting and reimagining an in-person qualitative research methods assignment to a web-based learning environment.

Outside the scope of COVID-19, our study adds to the literature on qualitative research. Research is sparse regarding the facilitation and implementation of web-based qualitative research methods courses [4,10]. We provide an example of a web-based qualitative research methods assignment, but the scope of this study goes beyond this assignment. Due to the pressure of the COVID-19 pandemic to rapidly adapt to web-based learning, our study helps demonstrate how this can be done while still meeting learning objectives. This study can be used as a starting point for instructors who wish to adapt qualitative courses for web-based learning or for instructors who have been forced to do so given the pandemic-related constraints.

In their rapid communication opinion piece, Neuwirth et al [32] argued that in the face of the COVID-19 pandemic, higher education instructors should be adapting and preparing for a "new normal" as opposed to a "return to normal." That is, the uncertainties that come with the pandemic should lead instructors to "re-envision" and "reimagine" how curriculums are designed and delivered to students [32]. We can adapt by embracing the new normal instead of resisting it. Our findings demonstrate that our video game observational assignment is consistent with this call to action. Furthermore, the observational assignment incorporated aspects of student engagement, interaction, and peer-to-peer instruction (ie, individual and group aspects and discussion boards for students to compare their experiences and observations), which are both important features (student engagement and interaction and peer-to-peer instruction) in a web-based environment [11,32,40]. These features allowed students to further engage with others and the assignment, solidifying their knowledge and skills for observational research.

Neuwirth et al [32] also stressed the importance of considering the economic and pragmatic burdens or constraints students face because of the pandemic. These burdens and constraints can realistically impact students' abilities to fulfill class requirements. Pandemic constraints were hastily considered when reimagining the format of the observational assignment. From a pragmatic standpoint, we realized that we could not require the students to venture out into a public area to conduct their assignment. We also realized that economic constraints must be considered, which was one of the reasons why the assignment was prerecorded. The recorded video game segment was of no cost and required no additional software to be purchased. Thus, efforts were made to circumvent pandemic constraints.

We demonstrated how a web-based method for delivering a qualitative assignment can be successfully implemented in a qualitative research methods course to meet learning objectives, providing additional support for such an assignment. This aligns with a study that investigated the use of *Second Life*, a 3D web-based environment, for teaching qualitative research methods. As part of this study, students conducted web-based observations and interviews via the *Second Life* platform as a simulation for conducting ethnographic research [10]. The results indicated *Second Life* is an innovative approach to teaching qualitative research methods, especially regarding a qualitative course delivered on the web. Two recently published articles have presented similar experiences with the web-based delivery of educational escape room assignments. Both articles found that the learning objectives for their classrooms were met

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when using digital escape rooms to teach concepts, such as problem-based learning, and that they (the two articles' instructional designs mentioned earlier in the paragraph) "promote engagement, active learning, and teamwork" [41,42]. They also found that these strategies for digital instruction can use student-centered approaches [41]. Web-based methods for assignment delivery are ideal for the current COVID-19 learning environments.

Lessons Learned

Although our study only focused on only one of the aspects of our course, we would be remiss not to include the lessons learned from our overall experiences with converting this face-to-face qualitative research methods course into a web-based course. As many institutions spend large portions of their curriculums focusing on quantitative research methods, students are often overwhelmed by an entirely new way of critical thinking that encompasses qualitative research. Students desire more synchronous opportunities to discuss readings and assignments and practice data analysis. This interaction can easily be added to a web-based synchronous qualitative course using Zoom videoconferencing (Zoom Video Communications), Microsoft Teams (Microsoft Corp), etc. This study presents numerous opportunities within the realm of qualitative teaching pedagogy, including improvements to the assignment examined in this study. In fact, the instructor has begun to adapt the course from the lessons learned while teaching on the web during the pandemic.

Readings for qualitative research can be dense and difficult to understand, especially when learning qualitative methods first. For future courses, the instructor will post readings and other material on the Perusall learning platform, allowing students to add comments and questions to readings, and see and respond to students' responses [43]. Perusall also allows instructors to see where students spend the most time reading and provides statistics on areas of the material that students may not grasp. This allows instructors to elaborate on and expand on these areas. Adding this feature to the course directly gives students additional opportunities to engage in and discuss material.

Discussion board assignments in this course did not receive positive feedback from the students, except for the observational research assignment described in this study and another assignment that gave the students data to practice coding (qualitative data analysis). Both activities show that the students appreciate discussion boards that allow them to acquire "hands-on" experience with qualitative research methods and then partner with other students to discuss and reflect on what they have learned. Furthermore, the students' responses suggest that interaction with the instructor and fellow students on discussion boards is important [40]. Qualitative courses should incorporate opportunities for students to acquire hands-on practice in different aspects of qualitative research.

Limitations

The current limitations of this study include its small sample size. This course is an advanced-level doctoral course; therefore, small class sizes are typical. Second, as data were collected from an upper-level doctoral course, the results may not be applicable to qualitative courses whose curriculums are developed for undergraduate students. Although this assignment was developed for doctoral students, we believe that it would also be accessible to undergraduate students with minor adaptations.

Conclusions

Research on the delivery of qualitative research methods courses using web-based learning environments is still in its infancy. We explored whether a pilot web-adapted video game qualitative observational research assignment successfully met the learning objectives of the qualitative research methods course and examined the students' perceptions of the adapted assignment. While our study provides insights into 1 adaptation of a qualitative assignment, it demonstrates that web-based environments can be used to meet qualitative research learning objectives and adds to our understanding of pedagogical practices for the web-based delivery of qualitative research methods courses. Furthermore, we demonstrate how the assignment aligns with the constructivist learning theory and other successful COVID-19 implementations. With the current pandemic and the resulting digital transformation, it is important to develop methods for an engaging, efficient, and effective delivery of qualitative content and the mastery of qualitative skills without relying on traditional in-person techniques.

Conflicts of Interest

None declared.

Multimedia Appendix 1
COVID-19 pandemic–adapted assignment.
[DOCX File , 15 KB - games_v10i4e38417_app1.docx]

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Abbreviations

ASSURE: Assure Learners, State Standards & Objectives, Select Strategies, Technology, Media & Materials, Utilize Technology, Media & Materials, Require Learner Participation, and Evaluate & Revise
IRB: institutional review board
UF: University of Florida

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Viewpoint

Are Conventional Combined Training Interventions and Exergames Two Facets of the Same Coin to Improve Brain and Cognition in Healthy Older Adults? Data-Based Viewpoint

Jean-Jacques Temprado[1*], PhD; Marta Maria Torre[1*], PhD

Aix Marseille Université, Institut des Sciences du Mouvement, Marseille, France

[*]all authors contributed equally

Corresponding Author:
Jean-Jacques Temprado, PhD
Aix Marseille Université
Institut des Sciences du Mouvement
163 Avenue de Luminy
BP 910
Marseille, 13288
France
Phone: 33 611837288
Fax: 33 491172256
Email: jean-jacques.temprado@univ-amu.fr

Abstract

Combining physical, motor, and cognitive exercises is expected to be effective to attenuate age-related declines of brain and cognition in older adults. This can be achieved either by conventional interventions or by exergames. This paper aimed to determine whether conventional combined training and exergame interventions are two comparable ways for delivering combined training. In total, 24 studies on conventional training and 23 studies on exergames were selected and compared. A common framework was used to analyze both types of combined training interventions. Our analysis showed that conventional combined training interventions were more effective than separated physical and motor training to improve brain and cognition, while their superiority over cognitive training alone remains to be confirmed. Exergames scarcely led to cognitive benefits superior to those observed after physical, motor, or cognitive training alone. Thus, although both conventional training interventions and exergames allowed delivering combined training programs, they are not two facets of the same coin. Further studies that are more theoretically grounded are necessary to determine whether interventions delivered via exergames may lead to superior benefits compared to conventional separated and combined training interventions.

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KEYWORDS

aging; older; gerontology; exergame; physical activity; cognition; training; intervention; cognitive; brain; older adult; motor skills; exercise; physical; motor; combined training

Introduction

Delaying or attenuating age-related cognitive decline is critical for preserving autonomy and quality of life of the increasing number of older adults. It has been widely demonstrated that separate cognitive, aerobic, muscular, and motor training are effective in this respect [1]. Moreover, it has been suggested that their integration into combined training interventions (CTIs) might be more effective than separated training [2-4]. In this context and in view of the role played by cognitive stimulations in CTIs [5,6], exergames (ie, interactive video games that require participants to be physically active to play) might be even more effective than conventional combined training programs, since they conjugate the effects of physical and motor exercises [1,7] and those of video game training on cognitive performance [8,9]. However, until now, no study has systematically compared, within the same experimental protocols, the respective benefits of ‘conventional’ CTIs and exergames with regard to cognitive outcomes in healthy older adults. “A review of reviews” (ie, 3 reviews on conventional cognitive and motor training and 3 on exergames) [10] recently addressed this issue and reported conflicting results. Specifically, the benefits of conventional CTIs were found superior to those of separated training in 2 reviews, but the superiority of exergames over

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physical or cognitive training alone was unclear in the selected reviews.

This paper aims to go a step further by reporting the results of a detailed comparison of studies that used conventional CTIs and those that used exergames to improve brain and cognition in healthy older adults. To fulfill this objective, based on the framework developed in 2 recently published review papers dedicated to conventional CTIs [11] and exergames [12], we compiled the data of 47 studies to compare randomized controlled trials and controlled trials that have used either conventional combined training or exergames to improve cognitive functions (Table 1 and Table 2).

Table 1. Selected reviews and studies on conventional combined training interventions. Studies were classified as a function of the type of combined intervention.

Conventional combined training interventions	Studies
Reviews	Law et al [13], Wollesen and Voelcker-Rehage [14], Zhu et al [15], Lauenroth et al [3], Levin et al [16], Tait et al [17], Gheysen et al [2], Joubert and Chainay [18], Gavelin et al [19], Wollesen et al [20], Gallou et al [10], Gou et al [21]
Studies	
Sequential	
PCT[a]	Fabre et al [22], Legault et al [23] Shatil et al [24], Linde and Alfermann [25], Shah et al [26], Mc Daniel et al [27], Desjardins-Crépeau et al [28]
MCT[b]	Oswald et al [29]
MDT[c]	Pieramico et al [30], Van het Reve and de Bruin [31], Rahe et al [32], Rahe et al [33], Kalbe et al [34]
Simultaneous	
PCT	Theill et al [35], Leon et al [36], Norouzi et al [37], Eggenberger et al [38], Eggenberger et al [39]
MCT	Hiyamizu et al [40], Marmeleira et al [41], Falbo et al [42]
MDT	Ansai et al [43], Yokoyama et al [44], Nishiguchi et al [45], Jardim et al [46]

[a]PCT: physical-cognitive training.

[b]MCT: motor-cognitive training.

[c]MDT: multidomain training.

Table 2. Selected reviews and studies on exergames. Studies were classified as a function of the type of combined intervention.

Exergames interventions	Studies
Reviews	Zhang and Kaufman [47], Bleakley et al [48], Ogawa et al [49], Howes et al [50], Stanmore et al [51], Vázquez et al [52], Mansor et al [53], Stojan and Voelcker-Rehage [54], Gallou-Guyot et al [10], Wollesen et al [20], Gavelin et al [19], Sakaki et al [55], Soares et al [56]
Studies	
Sequential	
PCT[a]	—[b]
MCT[c]	Park and Yim [57]
MDT[d]	Kayama et al [58]
Simultaneous	
PCT	Anderson-Hanley et al [59], Barcelos et al [60]
MCT	Schoene et al [61], Schoene et al [62], Gschwind et al [63], Schättin et al [64], Adcock et al [65], Carrasco et al [66], Eggenberger et al [39], Eggenberger et al [67], Huang [68], Li et al [69]
MDT	Maillot et al [70], Chuang et al [71], Ordnung et al [72], Guimaraes et al [73], Htut et al [74], Bacha et al [75], Peng et al [76], Moreira et al [77], Gouveia et al [78]

[a]PCT: physical-cognitive training.

[b]Not available.

[c]MCT: motor-cognitive training.

[d]MDT: multidomain training.

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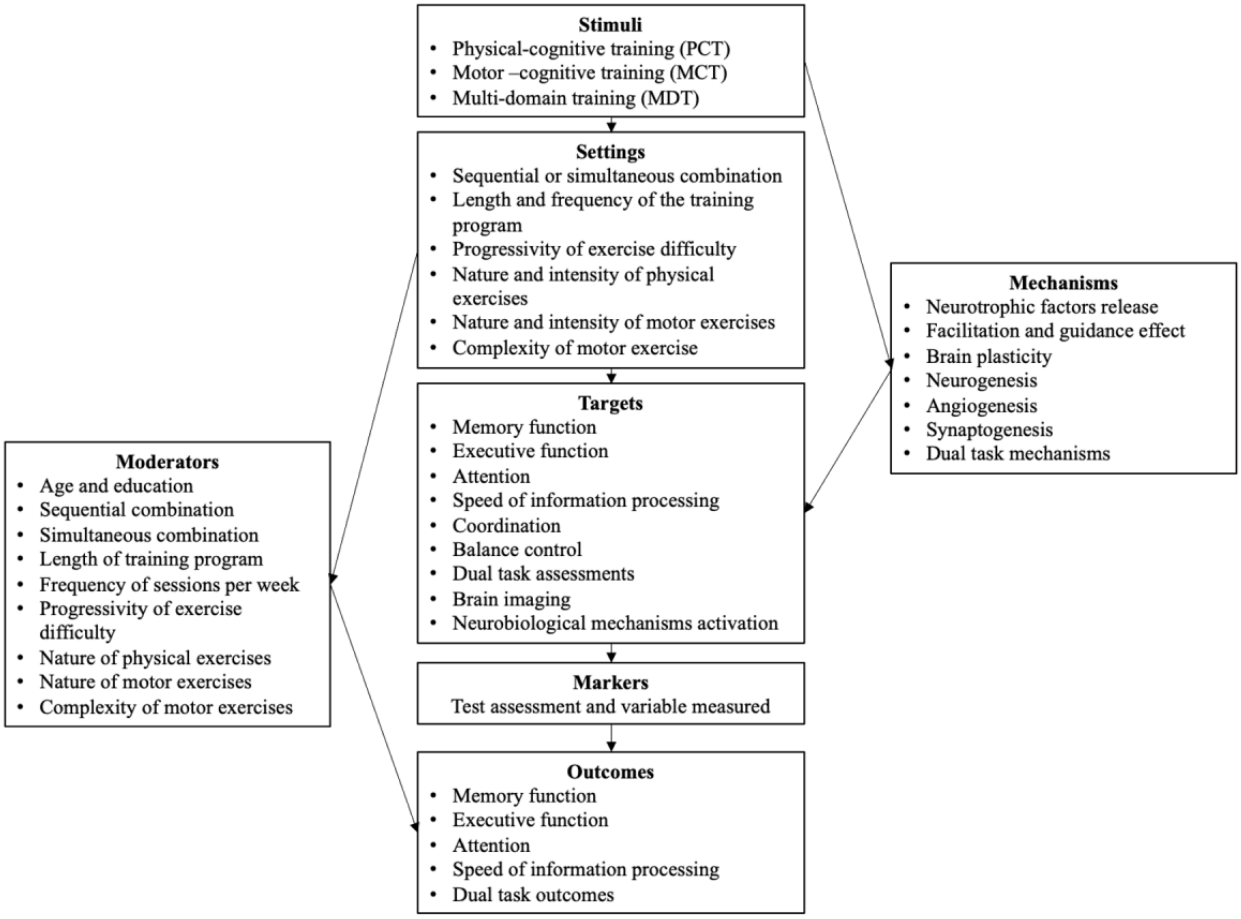
A Structured Framework for Analyzing Combined Training Interventions

We developed a framework to analyze CTIs, independent of whether they were delivered via conventional interventions or via exergames. Specifically, we distinguished the following: (1) the stimuli, which refer to different types of combined training; (2) the settings, which are the organizing features of training programs (ie, frequency, duration, intensity, instructions, feedback, individualization, and progressivity of increase in difficulty); (3) the targets of training, which were limited in this review to brain and cognitive levels, but other levels could be added in future works; (4) the markers, that is, the tasks and tests used to train or assess the participants, respectively; (5) the outcomes of different types of training, that is, the different variables that allow for quantifying the observed effects at brain and cognitive levels; (6) the moderators, who modulated the effects of training; and (7) the potential mechanisms, which were explicitly mentioned in different studies to predict and explain the effects of combined training (Figure 1).

Accordingly, 3 main training modes were distinguished: (1) physical-cognitive training (PCT), which correspond to the association of endurance (aerobic) and muscular resistance training and cognitive training, either sequentially or simultaneously; (2) motor-cognitive training (MCT), which refers to the association of complex motor skills training and cognitive training, implemented through the addition of cognitive tasks separated from the motor tasks (eg, mental calculation); and (3) multidomain training (MDT), which consists of associating aerobic exercises, complex motor skills, and cognitive tasks through laboratory-customized training situations. Notably, for conventional CTIs, we limited our analysis to randomized controlled trials and controlled trials in which it was possible to identify different training components (ie, physical, motor, and cognitive) that were associated with each other. Thus, according to this criterion, interventions implemented through natural motor activities (eg, tai chi, dance, or Nordic walking) were excluded. Although these activities included physical, motor, and cognitive components, their respective weights and levels of intensity or complexity were difficult to quantify. Based on this framework, in this study, we focused our comparative analysis on the following 4 main constructs: stimuli, settings, targets, and outcomes.

Figure 1. A multidimensional framework to analyze combined training interventions (detailed explanations are presented in a previous study [11]). Published under Creative Commons Attribution 4.0 International License.



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The Database

Our analysis was grounded on the material included in 2 recently published reviews dedicated to conventional CTIs [11] and exergames [12], respectively. Specifically, 24 studies on conventional training and 23 studies on exergames, published from 2010 to November 2021, were selected on the basis of several criteria [11,12]. These studies were then analyzed to compare them according to the 4 chosen constructs of our framework (Table 1 and Table 2).

Quantitative and Qualitative Differences Between Conventional Interventions and Exergames

Stimuli

Motor and cognitive exercises were performed simultaneously in 100% (n=23) of the exergames studies, whereas sequential presentation of physical and cognitive exercises was used in 58% (7/12) of conventional PCT studies, 22% (2/9) of MDT studies, and 50% (2/4) of MCT studies. Thus, one can hypothesize that several studies on conventional CTIs used mechanisms that were different from those involved in exergame interventions. Another important issue concerns the distribution of the 3 training modes (ie, PCT, MCT, and MDT), which differed in conventional CTI and exergames studies. Indeed, the proportion of PCT studies was much higher for conventional interventions compared to exergaming (12/24, 50% and 2/23, 8%, respectively), whereas the inverse was observed for MCT 16% (4/24) for conventional interventions and 47% (11/23) for exergaming, respectively) and MDT studies 37% (9/24) for conventional studies and 43% (10/23) for exergaming, respectively). This resulted from the predominant use of commercial exergames (eg, Xbox Kinect and Wii Balance Board), which were cheaper than the stationary cybercycle used for implementing PCT in exergames studies [59,60]. It could be concluded from the distribution of PCT in both conventional and exergaming intervention studies that, on average, the latter was less physically demanding than the former; supporting evidence could be found in a study by Graves et al [79], and a discussion is presented in Gonçalves et al's 2021 study [80]. However, this issue is a matter of debate, since few studies demonstrated that commercial exergames can be the support of intense physical activity [81,82], whereas others showed that they only facilitated light- to moderate-intensity physical activity [83]. On the other hand, since commercial exergames usually required upper limb movements, whole body movements, stepping, weight shifting or balance control, motor exercises supporting MCT and MDT in conventional CTIs and exergames studies were roughly similar.

Settings

Conventional CTIs most frequently aimed to compare several groups simultaneously. Indeed, 21/24 (87%) involved a passive control group, alone or together with cognitive training (15/24, 62%) and physical or motor training (13/24, 54%) groups. In total, 8/24 (33%) of the conventional training studies involved 3 training groups (ie, CTI, physical or motor, and cognitive), whereas it was the case in only 1/23 (4.3%) of the exergames studies. Most frequently, exergames studies included 2 groups, that is, either a passive control group (9/23, 39.1%), a physical or motor training group (13/23, 56.5%), or less frequently, a cognitive training group (2/23, 8.6%), in addition to the exergaming group. In both conventional CTI and exergames studies, permanence and transfer of training effects were scarcely investigated, so no reliable conclusion can be drawn in this respect.

Targets

No main difference was observed between the cognitive abilities tested in conventional CTIs and exergames studies. The most frequently tested were memory, executive functions, attention, and information processing speed, but there were no 'a priori' assumptions about the type of functions that could be affected more or less by each CTI. The respective effects of conventional combined training and exergames on brain health and neurobiological mechanisms cannot be reliably compared due to the small number of related studies and their heterogeneity (ie, 4 and 2 studies, respectively).

Outcomes

Combined Training Versus Passive Control Groups

Independent of the training modes (ie, PCT, MCT, or MDT), positive effects were observed, relative to passive control groups, in all conventional CTIs and exergames studies, for at least one of the targeted cognitive functions, that is, memory, attention, executive functions, and information processing speed. These results were observed for both sequential and simultaneous associations between cognitive and physical or motor exercises. Unfortunately, it was impossible to determine whether cognitive functions were differently impacted by conventional combined training and exergames, respectively. These results are consistent with those reported by Gallou-Guyot et al [10]. Unsurprisingly, they suggest that regardless of how combined training is delivered (ie, conventional interventions or exergames, and PCT, MCT, or MDT), combined training programs always lead to superior benefits compared to inactivity.

Combined Training Versus Physical Training

In conventional CTIs, superior benefits of combined training over separated physical training were observed in 100% (n=13) of MCT and MDT studies and in most of the PCT studies (8/12, 66.6%). On the other hand, superior benefits of exergaming compared to conventional physical or motor training alone were observed in only one study on exergames [59], whereas no difference was found between the exergames and separated training groups in the 4 other studies (2 on MCT and 2 on MDT).

Combined Training Versus Cognitive Training

In conventional training studies, compared to cognitive training alone, superior benefits of CTIs were observed in almost one-third of PCT studies (n=4), but never in MCT and MDT studies. In the 2 studies that compared exergaming and cognitive training, one reported a superiority of the former over the latter on executive functions [67], whereas the other did not [74].

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Thus, the number of related studies was too small to draw reliable conclusions about the superiority of exergames over cognitive training alone.

Limitations and Study Comparisons

The studies including 4 training groups (ie, combined training, separated physical and cognitive training, and a control group), which could allow for a complete comparison, were scarce (ie, 8 conventional training studies out of 47, in total). A second observation was that despite the type of intervention (ie, conventional or exergames), the mechanisms underlying eventual differences with physical and cognitive training groups were rarely addressed in the reviewed studies. A third observation was that information relative to intensity and the nature of physical exercises, the nature and levels of complexity of motor exercises, and progressivity of difficulty was neglected in most studies, so it was impossible to estimate why physical or motor training was effective (or not) to improve physical, motor, or cognitive performance. This was the case, in particular, in exergames studies. In addition, in several studies, cognitive training procedures and (exer)game contents were not described or were only superficially described. Finally, due to the small number of studies available to support some comparisons (eg, exergames and cognitive training; conventional CTI vs exergames), the results remain to be confirmed or even established in future studies.

Discussion

In this paper, we aimed to determine whether conventional CTIs and exergames were two comparable ways for delivering combined training. Our analysis showed that conventional CTIs were more effective than separated physical and motor training to improve brain and cognition, but their superiority over cognitive training alone remains to be confirmed in further studies. On the other hand, exergames scarcely led to cognitive benefits superior to those observed after physical, motor, or cognitive training alone. A plausible reason is that the existing exergames did not allow reaching high enough levels of physical effort [10] or motor skills complexity, and they used the resources of virtual reality and video games insufficiently to improve the cognitive load of different exercises [84]. This is not to say that exergame interventions cannot succeed in being more effective than conventional CTIs. However, further studies, grounded on theoretical knowledge provided by the literature on physical, motor, and cognitive training are necessary to determine whether interventions delivered via exergames may lead to superior benefits compared to separated and combined CTIs. In particular, since commercial exergames are not designed specifically for older adults, exergames studies should use new solutions that are more grounded on theoretical foundations [84].

Finally, this analysis showed that conventional CTIs and exergames studies did not address the same research questions, thereby precluding reliable comparisons of their benefits. Specifically, conventional CTI studies prominently aimed to compare benefits of separate training programs, whereas exergames studies focused on the benefits of exergaming per se, most often relative to inactive control groups. Thus, contrarily to our expectations, they seem to be separated domains of the literature on aging, which, until now, have developed independently of each other. In particular, the literature on exergames has not yet reached the level of maturity of those on conventional CTIs, which itself remains heterogeneous and suffers from methodological weakness and lack of a strong conceptual background [11,84,85]. Therefore, although they both allow for delivering combined training programs, conventional and exergames interventions are not two facets of the same coin; rather, they are two coins we do not know which is more valuable. Accordingly, future studies should aim to develop new exergames that would capitalize more on the knowledge from studies on conventional CTIs, particularly concerning the underlying mechanisms. These studies should also systematically compare the effectiveness of existing or new exergames and that of conventional CTIs.

Conflicts of Interest

None declared.

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Abbreviations

CTI: combined training intervention
MCT: motor-cognitive training
MDT: multidomain training

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PCT: physical-cognitive training

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Original Paper

Handheld Weights as an Effective and Comfortable Way To Increase Exercise Intensity of Physical Activity in Virtual Reality: Empirical Study

Jacek Polechoński[1], PhD; Anna Zwierzchowska[1], PhD, DSC; Łukasz Makioła[2], MSc; Dorota Groffik[1], PhD, DSC; Karolina Kostorz[1], PhD

[1]Institute of Sport Sciences, The Jerzy Kukuczka Academy of Physical Education in Katowice, Katowice, Poland

[2]Student Scientific Circle of Physical Activity and Tourism in Virtual Reality "ACTIVE VR", The Jerzy Kukuczka Academy of Physical Education in Katowice, Katowice, Poland

Corresponding Author:
Jacek Polechoński, PhD
Institute of Sport Sciences
The Jerzy Kukuczka Academy of Physical Education in Katowice
72A, Mikołowska St
Katowice, 40-065
Poland
Phone: 48 32 207 51 93
Email: j.polechonski@awf.katowice.pl

Abstract

Background: In recent years, there has been a growing interest in active virtual reality games (AVRGs) that provide entertainment and encourage more physical activity (PA). Since playing AVRGs involves primarily arm movements, the intensity of this form of PA may not be sufficient for health benefits. Therefore, it is worth looking for virtual entertainment solutions that are comfortable for users and at the same time increase physical exercise.

Objective: The main objective of this study was to evaluate the effect of external loading of the arms in the form of handheld weights (HHWs) on exercise intensity in users playing a popular AVRG. The results obtained in the study were compared with the PA recommendations for health. The study also assessed the perceptions of the users about the attractiveness and usefulness of this type of exercise and discomfort caused by additional load on the arms.

Methods: The study covered 17 young adults aged 18 to 25 years playing an AVRG (Beat Saber) with no arm load and with HHWs (0.5 kg). A PlayStation 4 PRO console (Sony) with accessories including a head-mounted display and controllers was used in the study. PA intensity was evaluated using a heart rate monitor based on the percentage of maximal heart rate (% HR_{max}). The usability, attractiveness, and comfort perceived during exercise by users were evaluated using a survey questionnaire.

Results: The measurements showed that the mean % HR_{max} in participants playing Beat Saber without HHWs was significantly lower ($P<.001$; Cohen $d=1.07$) than that observed when playing with HHWs. It should be emphasized that with no additional load, the intensity of PA was low (mean 63.7% HR_{max}, SD 9.3% HR_{max}), while with the upper limb load, it increased to a moderate level (mean 67.1% HR_{max}, SD 10.3% HR_{max}), which is recommended for health benefits. The survey conducted in the study showed that HHWs (0.5 kg) attached to the wrists did not disturb Beat Saber players.

Conclusions: Since PA in most of the modern AVRGs primarily involves upper limb movements, the use of HHW seems to be a simple and effective way to increase exercise intensity, especially because, as reported by the study participants, such a procedure does not cause discomfort while using the application.

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KEYWORDS

immersive virtual reality; virtual reality; health-related physical activity; intensity of physical activity; active video games; serious games

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Introduction

The last decade has seen unprecedented advances in immersive virtual reality (VR) [1]. There is no doubt that technology has revolutionized the way the user interacts with the digital world. Nowadays, with modern head-mounted displays (HMDs) and custom software, this state-of-the-art technology simulates a real-world environment by providing the user with 3D experience without discomfort [2]. Increasing computing power, improved graphics, greater processing speed, and better internet connectivity have resulted in better access and higher consumer demand for VR [3]. Consequently, VR technology is increasingly being used in various areas of life and science, including health care, rehabilitation, psychology, education, engineering, manufacturing, and entertainment [2,4-10]. The development of information technology and the ever-increasing popularity of video games are often associated with the reduction of a person's physical activity (PA) in favor of prolonged sitting in front of a computer, resulting in poor well-being and progressive deterioration in the physical and mental health status [11-14] Therefore, in recent years, there has been a growing interest in active virtual reality games (AVRGs), which provide entertainment and encourage PA [15-25]. AVRGs are video games that require users to perform physical exercise [26].

Not surprisingly, there has been a steady increase in the number of scientific studies that verify, compare, and discuss interventions using VR. With the development of modern civilization and sedentary lifestyles, the use of VR in sports and in promoting PA is particularly important [15,27-30]. However, the level of PA intensity is extremely important to achieving health benefits. According to the guidelines of the World Health Organization (WHO), PA intensity should be at least moderate [31]. However, published research findings are inconclusive. Some researchers point to moderate to high levels of exercise intensity in those playing AVRGs, especially when using exercise machines (eg, cycle ergometers, treadmill) [16,18,19,22,23]. Locomotion has been shown to promote exercise intensity and enhance the immersion experience. Consequently, research has been undertaken to analyze physical exercise in VR [32-35]. It was found that exercise intensity using exercise machines in VR can be higher compared to similar PA during conventional training sessions [20].

There are also reports that PA in VR is characterized by rather low intensity, especially when the game is played using room-scale tracking, in which the user moves in a limited space, and movements are mainly performed with the upper limbs [36]. Unfortunately, this is the most common way to use HMDs. The question arises: What can be done to increase PA intensity when using movement applications in VR without having to use expensive and bulky indoor trainers? Given that standard controllers are operated primarily by arm movements, it was assumed that a simple solution might be to add a small additional load on the upper limbs using Velcro-fastened handheld weights (HHWs) on the wrists. This concept inspired the experiment described in this paper. It should be added that sets of weights fastened with Velcro are popular equipment used in various forms of PA, such as aerobics, jogging, general fitness exercises, and rehabilitation [37-39]. However, to date, HHW has not been used in studies on physical exercise intensity in VR.

Considering all of the aforementioned issues, the main aim of this study is to evaluate the effect of external arm loading on the intensity of PA in young adults playing a popular AVRG (Beat Saber). It was assumed that the use of HHW would facilitate the achievement of PA intensity at the level recommended for health benefits. Another assumption was that the load applied would not reduce the player's perception of comfort during the game.

Methods

Participants

The study was conducted on a group of 17 participants aged 18 to 25 years: 7 women (mean age 20.7 years, SD 2.6 years; mean body height 169.9 cm, SD 6.3 cm; mean body weight 62.4 kg, SD 7.7 kg) and 10 men (mean age 19.6 years, SD 2.0 years; mean body height 174.7 cm, SD 7.8 cm; mean body weight 60.2 kg, SD 7.7 kg). They were recruited from participants of the Silesian Festival of Science held at the International Convention Center in Katowice, Poland, where hardware and software that allow players to perform PA in VR were presented. We selected a group of young adults who volunteered to participate in the study, were able to use VR technology, and did not require additional training in the use of VR equipment. It should also be noted that people of this age are the most frequent users of VR headsets. All participants signed a consent to participate in the experiment and were informed about the purpose and procedures of the study. Furthermore, the following inclusion criteria were used: good general health status, no medical contraindications to participation in the study (specifically, no epileptic history or motion sickness), no physical limitations (eg, injuries) that might restrict PA in VR, and not taking any agents that affect heart rate.

Ethics Approval

The study was conducted according to the guidelines of the Declaration of Helsinki and reviewed and approved by the Research Ethics Committee of the Jerzy Kukuczka Academy of Physical Education in Katowice (protocol #9/2018). All participants took part in the study voluntarily and could discontinue their participation at any time.

Research Tools and Procedures

The PlayStation 4 PRO console (Sony) with accessories including an HMD and controllers was used in the study. The HMD, worn on the participant’s head, was used for displaying VR, while the controllers held in the hands allowed the participant to control the game. Figure 1 presents the user using the application. PA was evaluated during playing of the Beat Saber game, in which the player cuts through virtual cubes coming toward him or her with lightsabers to the beat of the music. The cutting direction is indicated by the arrows displayed on the objects. The moving cubes come in 2 colors, as do the virtual lightsabers held by the user. The participants played at the same difficulty level (normal) with an additional no-fail option to facilitate the procedure and ensure game continuity even after the number of mistakes allowed in the basic

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configuration had been exceeded. Furthermore, the no-arrow option was used for convenience to remove arrows from blocks and allow objects to be cut in any direction (Figure 2). The music track “Crab rave” was used and played in a loop to suit a 10-minute training session. Prior to the game, participants were trained on how to use the equipment and the application. The research procedure consisted of two 10-minute sessions of playing active video games. Each player participated in alternating sessions with and without arm loading. The order of sessions was counterbalanced. Every second person started the session with weights. There was a 30-minute rest between sessions. A 0.5-kg HHW fastened at the wrist of the right and left upper limbs was used to load the arms (Figure 3).

Figure 1. Participant playing an active video game (Beat Saber) in immersive virtual reality with handheld weights.

Figure 2. Gameplay of the Beat Saber game: print screen.

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Figure 3. Handheld weights (0.5 kg) used in the study.

Heart rates were monitored during the playing of AVRGs using a Vantage V heart rate monitor (Polar Electro Oy). Exercise intensity was evaluated based on the average percentage of maximum heart rate (% HR_{max}) obtained by each participant during the test. Before the experiment, the participant's HR_{max} was calculated from the following formula: 208 – 0.7 × age in years [40]. Exercise load was estimated based on the exercise intensity classification proposed by the American College of Sports Medicine [41]. According to the classification, average HR (HR_{avg}) <64% HR_{max} is low intensity, 64% $HR_{max} \leq HR_{avg} <$ 77% HR_{max} is moderate intensity, and $HR_{avg} \geq$ 77% HR_{max} is high intensity. The data obtained using this classification were compared to the criteria of health recommendations for the intensity of aerobic exercise, according to which exercise of at least moderate intensity is considered beneficial for health (≥64% HR_{max}) [31]. Exercise intensity was also categorized into HR zones using the Polar Flow training analysis tool. The absolute time (in seconds) of HR spent in each of the following six zones was estimated as follows: I, <50% HR_{max}; II, 50%-59% HR_{max}; III, 60%-69% HR_{max}; IV, 70%-79% HR_{max}; V, 80%-89% HR_{max}; and VI, ≥90% HR_{max}. Calculations were performed for both training sessions to compare exercise intensity. The perceived exertion was estimated using the Borg Rating of Perceived Exertion (RPE) 6-20 scale [42], and its correlation with objective measurements was assessed.

After the completion of both games, our survey questionnaire consisting of 8 items (Table 1) was administered to gain information about the participants' subjective perceptions of the attractiveness and usefulness of PA in VR and their comfort of exercising with HHWs. A 7-point Likert scale was used in the evaluation of the questionnaire. The respondents could choose between the following answers: "Strongly disagree," "Disagree," "Somewhat disagree," "Neither agree nor disagree," "Somewhat agree," "Agree," and "Strongly agree."

Table 1. Users' opinions on the attractiveness and usability of the Beat Saber game and the comfort of playing with HHWs (N=17).

Question	Strongly disagree, n (%)	Disagree, n (%)	Somewhat disagree, n (%)	Neither agree nor disagree, n (%)	Somewhat agree, n (%)	Agree, n (%)	Strongly agree, n (%)
1. Was playing VR[a] attractive and enjoyable for you?	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	8 (47)	9 (53)
2. With the right hardware and software, would you regularly practice PA[b] in VR?	1 (6)	0 (0)	0 (0)	0 (0)	1 (6)	8 (47)	7 (41)
3. Would you recommend practicing PA in VR to others?	0 (0)	0 (0)	0 (0)	0 (0)	2 (12)	11 (65)	4 (23)
4. Do you think that practicing PA in VR is more enjoyable than performing conventional training exercises?	0 (0)	1 (6)	1 (6)	5 (29)	0 (0)	5 (29)	5 (29)
5. Do you think practicing PA in VR can complement a person's leisure-time PA?	0 (0)	0 (0)	1 (6)	1 (6)	4 (23)	5 (30)	6 (35)
6. Do you think practicing PA in VR can satisfy a person's needs for leisure-time PA?"	0 (0)	0 (0)	2 (12)	2 (12)	3 (18)	8 (47)	2 (12)
7. Do you think practicing PA in VR can replace typical real-world forms of leisure-time PA?	1 (6)	1 (6)	5 (29)	2 (12)	7 (41)	1 (6)	0 (0)
8. Did you experience any discomfort while playing with HHW[c]?	12 (71)	2 (12)	2 (12)	0 (0)	1 (6)	0 (0)	0 (0)

[a]VR: virtual reality.

[b]PA: physical activity.

[c]HHW: handheld weight.

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Statistical Analysis

Statistical calculations were performed using Statistica v. 13 software (TIBCO Software Inc). Measurement data were analyzed using basic descriptive statistics. The results of the survey are presented as percentages. Arithmetic means, SDs, and differences in means were calculated. The data were tested for normal distribution using the Shapiro-Wilk test, whereas the significance of differences was evaluated using the *t* test or Wilcoxon test. Cohen *d* effect size was also calculated with <0.2=trivial effect, 0.2-0.5=small effect, 0.5-0.8=moderate effect, and >0.8=large effect [43]. Pearson correlation analysis was used to assess relationships.

Results

PA Intensity During the Playing of an AVRG (Beat Saber) With and Without HHWs in Light of Health Recommendations

Heart rate measurements showed that the average heart rate (HR_{avg}) of Beat Saber users playing without HHW was 123.2 (SD 18.2) bpm and was significantly lower (P<.001; Cohen d=1.7) than that observed when playing with HHWs (mean 129.8 bpm, SD 20.2 bpm). A similar statistically significant relationship was observed when analyzing the average percentage of maximum heart rate (% HR_{max}). This parameter was also significantly lower (P<.001; Cohen d=1.07) when the arms were not loaded (mean 63.7% HR_{max}, SD 9.3% HR_{max}) than when participants played with HHWs attached to the wrists (mean 67.1% HR_{max}, SD 10.3% HR_{max}). It should be emphasized that in the conditions of no additional load, the intensity of PA was low, while with the upper limb load, it increased to a moderate level as recommended for health benefits (Figure 4).

During both 10-minute sessions, participants' heart rates remained for the longest time within the range of 60%-69% HR_{max}, which is optimal for fat reduction. When playing without HHW, the exercise at this intensity lasted 225.1 s whereas when playing with HHW on the wrists, users maintained this level of heart rate for 244.2 s. A comparison of the time spent in each heart rate zone in both sessions reveals that the greatest discrepancy was observed in zone IV (45 s). However, this difference was not statistically significant (Figure 5).

In the subjective perception of PA intensity made by study participants on the Borg RPE 6-20 scale, playing without HHWs was also reported to be significantly less intense (P=.004; Cohen d=–0.813) than playing with HHWs, with an average 11.0 (SD 3.2) points and 13.2 (SD 3.6) points, respectively (Figure 6). A comparison of these values with the classification of PA intensity [44] shows that the participants rated the intensity of exercise without HHWs as low and with HHWs as moderate, which was similar to the objective evaluation using a heart rate monitor. Furthermore, the analysis of correlations between subjective and objective measures of exercise intensity revealed a statistically significant (P<.001) high correlation (r=0.56) between intensity estimated based on % HR_{max} and the Borg RPE 6-20 scale for PA in VR with HHWs. In contrast, no such correlations were observed (r=0.08) when playing without HHWs.

Figure 4. Intensity of physical exercise during playing Beat Saber depending on arm loading. % HR_{max}: percentage of maximal heart rate; *d*: Cohen *d* value; HHW: handheld weight.

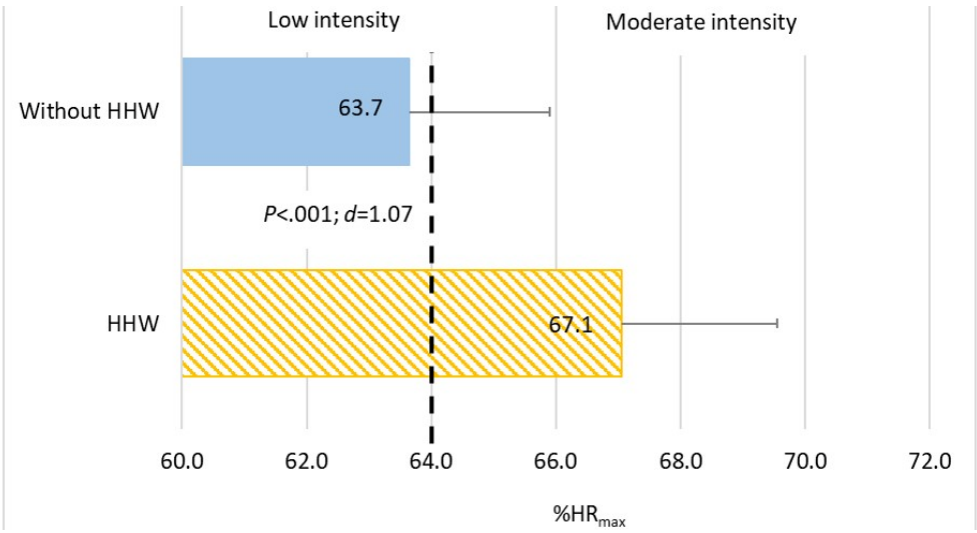

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Figure 5. Average total time spent in different heart rate zones by participants during playing Beat Saber games with and without arm loading. HHW: handheld weight; HR_{max}: maximal heart rate.

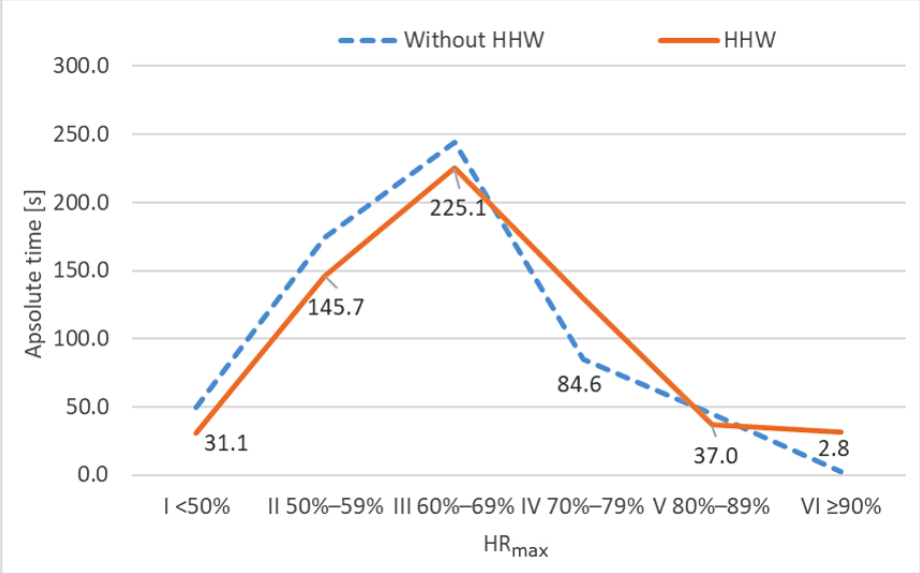
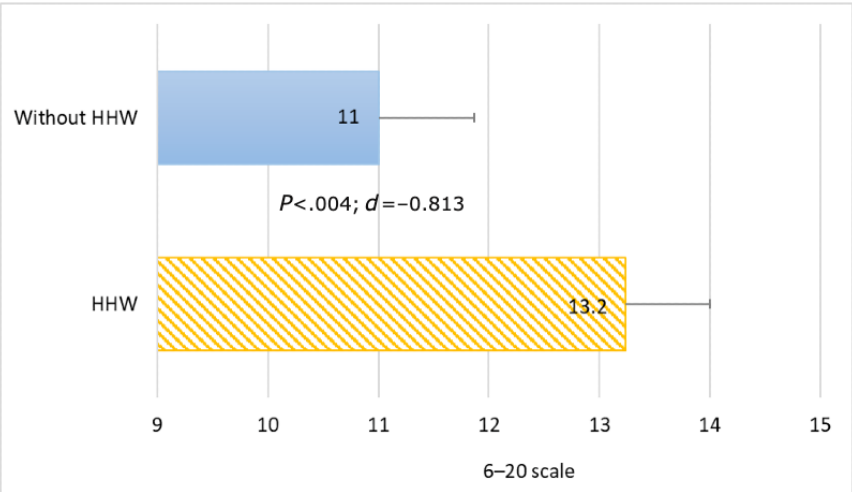


Figure 6. Rating of perceived exertion (6-20 scale) depending on arm loading. *d*: Cohen *d* value; HHW: handheld weight.



Attractiveness and Usability of an AVRG (Beat Saber) in the Opinion of Users and Comfort of Exercising With Loaded Arms

The results of the survey showed that the Beat Saber game was attractive and enjoyable for all study participants. This statement was agreed or strongly agreed upon by 100% (17/17) of the respondents. Nearly all (16/17, 94%) declared the willingness to be involved in regular PA using VR. Only 1 person was completely unwilling to do so. All respondents would or would rather recommend practicing PA in VR to others. Respondents were more divided in their opinions regarding the comparison of enjoyment of practicing PA in VR with conventional exercising. For the majority (10/17, 59%) of respondents, exercising in VR was more enjoyable than was conventional PA. The opposite view was held by 12% (2/17) of respondents. In contrast, 29% (5/17) of respondents did not express a clear opinion on this issue. Most respondents (14/17, 82%) believed that practicing PA in VR can complement a person's leisure-time PA. One respondent disagreed with this statement, and one had no opinion at all. To the question “Do you think practicing PA in VR can satisfy a person's needs for leisure-time PA?”, 76% (13/17) of respondents answered affirmatively. Furthermore, 12% (2/17) of respondents had no opinion on this issue, and 12% (2/17) disagreed with this statement. Almost half of the respondents (8/17, 47%) believed or tended to believe that practicing PA in VR could replace typical real-world forms of leisure-time PA, 12% (2/17) of the respondents were undecided on this issue, while the rest (7/17, 41%) had the opposite opinion. According to the survey, HHWs (0.5 kg) attached to the wrists did not disturb Beat Saber users. Only 1 player (1/18, 6%) had a rather different opinion (Table 1).

Discussion

Principal Findings

For several years, research has been conducted on the potential of active video games in engaging the musculoskeletal and cardiorespiratory systems as a health-promoting form of PA [16,22,45-47]. This is true for both nonimmersive and immersive

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VR applications, as AVRGs are a beneficial alternative to conventional video games, which are responsible for prolonged periods of sedentary behavior [48-51]. Furthermore, users from different age groups have indicated that such games are highly attractive and useful [15,20,25,52-54]. Unfortunately, many popular AVRGs are created to be used in a limited space, with controllers and HMDs primarily involving arm and torso movements while sitting or standing, which may translate into insufficient exercise intensity to provide health benefits. Although exercise intensity can be increased using trainers available on the market that are compatible with VR devices, their high prices and the required space limit their widespread use. Therefore, one should look for cheaper and more effective ways to increase PA intensity in VR.

To meet the aforementioned needs and expectations, it was hypothesized that a small additional load on the upper limbs of a 0.5-kg HHW and using a room-scale tracking mode would be a simple solution to increase the PA intensity of players. To our knowledge, no studies have been undertaken to date that have evaluated the effect of external arm loading on exercise intensity in young adults playing in VR. Bridging this gap in scientific research has been the direct objective of our analysis.

This study showed that the use of HHWs can be an effective solution. Relatively small and light weights (0.5 kg) contributed to a significant increase in PA intensity, expressed as an average % HR_{max} during playing Beat Saber, from low to moderate levels; that is, those recommended by the WHO for health benefits [31].

Although there is a lack of reports on exercising with HHWs in VR, our results can be related to studies of other forms of PA that have evaluated the effect of the external loading of the upper limbs on exercise intensity. Lee and Kim [55] demonstrated that the use of HHWs during exercise can increase the energy expenditure (EE) of upper body activity, which is extremely important for individuals with low fitness levels and special patient populations who cannot run, do not want to run, or have limited mobility of brisk walking. However, there are other studies in the available literature that do not support a significant effect of walking on a treadmill with HHWs on EE and other exercise parameters [37,38,56]. Furthermore, the use of heavier poles in Nordic walking was observed to have no effect on EE compared to Nordic walking with regular poles although greater muscle activity was reported [57]. However, it should be noted that Nordic walking has a higher EE compared to conventional walking [58]. This is probably largely due to the different ways of moving, but the weight of the poles held in the athlete's hands is probably nonnegligible.

One important aspect of our study was that participants made the subjective assessment of PA intensity using the Borg RPE 6-20 scale. It was found that playing without HHWs was perceived as significantly less intense than playing with HHWs. A comparison of the obtained values to the classification of PA intensity [59,60] shows that the participants rated the intensity of the exercise without HHWs as low and with HHWs as moderate. Therefore, the subjective perceptions of PA intensity made by the participants in this study were consistent with the objective evaluation using a heart rate monitor. This could indicate that users engaged in PA in immersive VR can accurately assess their fatigue. However, this is not supported by the correlation analysis between subjective perceptions and objective measurements. It was demonstrated that a statistically significant relationship between intensity scores estimated based on % HR_{max} and the Borg RPE 6-20 scale was only present for practicing PA in VR with HHWs (r=0.56; P<.001). When playing without HHWs, no correlation (r=0.08) was found between % HR_{max} and the Borg RPE 6-20 scores. Similar findings were reported in a study that evaluated PA in VR in obese children during the playing of 2 AVRGs using an omnidirectional treadmill [22]. In the aforementioned studies, the games were played without any additional load, and the results of the subjective perceptions and objective measurements of PA intensity did not correlate with each other although the children in the study were able to accurately assess which game was more intense for them. This is difficult to interpret conclusively although it is hypothesized that the use of light additional resistance in VR makes the subjective perceptions of fatigue more relevant to the actual one than when PA is performed without a load. This can be surmised from studies showing that VR reduces the intensity of various stimuli (eg, pain) by distracting attention from thinking about the problem [61-64]. This is associated with what is known as a cognitive distraction. Perhaps a similar effect occurs during PA and helps alleviate the discomfort associated with intense exercise. This could be important for people with reduced physical fitness and poorer physical capacity, as they would be able to perform longer and more intense exercises in VR. This thesis is indirectly confirmed by the aforementioned studies of obese children who, despite declared low physical fitness, were able to exercise in VR for several minutes at a very high intensity (83% HR_{max}) [22]. The usefulness of VR in distracting from unpleasant bodily sensations occurring during aerobic PA in overweight and obese children has also been demonstrated by other authors [65]. There are also reports indicating that VR reduces the negative sensations associated with performing isometric exercises, thus increasing the likelihood of performing them for longer periods of time [66]. Given the findings of these studies, there is much to suggest that VR may be useful in reducing the perception of exercise intensity and fatigue. However, providing unequivocal evidence for this phenomenon requires that further similar studies be undertaken.

The survey conducted in our study shows that the Beat Saber game was positively received by the respondents. All participants found it an attractive, enjoyable, and recommendable form of PA. Furthermore, almost all of them declared their willingness to regularly practice this form of PA in VR. The positive user reception of AVRGs has been also highlighted by other authors [16,22,52]. It is noteworthy that for the majority of respondents, PA in VR was more enjoyable than was conventional PA. Similar findings also emerged from another study that compared real-world and VR training on a cycle ergometer [18,20,25]. The participants reported having more fun riding a stationary bike in VR than in conventional conditions, which might have resulted from the gamification effect. Many studies have shown that satisfaction is an important predictor of engagement in PA regardless of participants' age

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or health status [67-72]. In this context, AVRGs can be considered a form of exercise that can complement a person's leisure-time PA and even satisfy their needs for physical exercise as indicated by the vast majority of respondents. Almost half of the respondents even claimed that PA in VR could replace typical real-world forms of leisure-time PA. It should be noted, however, that from the standpoint of inclusion, participation in social life, and the values of outdoor PA, it would be inadvisable to completely replace typical forms of PA in favor of those practiced in VR. Therefore, AVRGs should be considered complementary to conventional forms of PA.

An important aspect of the present study was also to assess any discomfort resulting from exercising with HHWs. According to the survey, additional HHWs (0.5 kg) attached to the wrists did not disturb Beat Saber players. Furthermore, given that it significantly increases PA intensity, HHW should be recommended for PA in VR based mainly on arm work. This can improve the effectiveness of the exercises and increase their health benefits. An important consideration here is the choice of the optimal load. This is because there is a concern that an excessive increase in exercise intensity during playing AVRGs may make playing less attractive. However, according to previous research, AVRGs that require more physical effort may be more appealing than may games characterized by lower-intensity exercise. For example, Dębska et al [16] examined user satisfaction with practicing PA in VR on the Omni omnidirectional treadmill and the Icaros flight simulator. Although exercise intensity was high in the former and low in the latter, the AVRG on the treadmill was rated higher in terms of attractiveness. Similar relationships have been observed in studies of obese children that compared the attractiveness of 2 AVRGs on a treadmill [22]. Again, higher PA intensity proved more attractive to users. This demonstrates that according to users, intense physical exercise in VR remains very attractive. To the best of our knowledge, which is based on our literature review, the research we conducted on the effect of HHWs on exercise intensity in VR can be considered novel. Although manufacturers of VR sets strive to minimize equipment and reduce its weight, it may be worth doing the opposite in some cases. Arm loading may be advisable not only to increase the intensity of exercise in VR, but also to enhance immersion (such as playing virtual tennis, baseball, or fighting with a heavy sword). Therefore, it seems warranted to undertake further multifaceted research on the effects of different sizes and different types of arm loading on the PA and the perceptions of players immersed in a virtual environment.

Limitations

There is no doubt that the results presented in the study have several limitations. Given the relatively small group of participants, the results should be treated with caution. A more precise method of evaluating exercise intensity, such as indirect calorimetry, would be useful in future studies. In the present study, % HR_{max} was used because it was feared that the masks used in calorimetry might cause discomfort and lead to the participant's underestimation of the subjective appeal of the game, making it difficult to assess the comfort of performing exercises with HHWs. Furthermore, the use of our author-made survey questionnaire in the study is also a limitation, as it makes it difficult to accurately compare the findings regarding the enjoyment and attractiveness of using AVRGs with those published in previous studies. However, it should be noted that the questionnaire was only an additional component of this study.

Conclusions

Our research, conducted on a group of young adults, showed that the AVRG Beat Saber is a form of PA that is attractive to users and can complement a person's leisure-time PA. It can also be a beneficial alternative to typical video games played in a seated position. With the additional loading of the participant's wrists using a small HHW (0.5 kg), the relatively low intensity of physical exercise when playing Beat Saber (a game based primarily on arm movements) significantly increased to a moderate level, which in the context of health-related recommendations should translate into health benefits. Since PA in most modern AVRGs primarily involves upper limb movements, the use of HHWs seems to be a simple and effective way to increase exercise intensity, especially because, as reported by the study participants, such a procedure does not cause discomfort while using the application. Our findings may provide guidance to VR equipment manufacturers on how to make exercise more effective in the playing of AVRGs. However, to confirm the above conclusions, further research is needed using various existing applications that allow for the performance of PA in an immersive virtual environment. Future research would also benefit from evaluating the effect of changing the magnitude of arm loading on exercise intensity in VR. The use of a different type of arm load (eg, in the form of elastic resistance) seems equally interesting. In conclusion, we recommend the use of a light arm load in the form of HHWs when practicing Beat Saber AVRGs, as this increases the intensity of PA, which may translate into health benefits.

Conflicts of Interest

None declared.

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Abbreviations

% HR_{max}: percentage of maximal heart rate
AVRG: active virtual reality game
EE: energy expenditure
HHW: handheld weight
HMD: head-mounted display
HRavg: average heart rate

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HR_{max}: maximum heart rate
PA: physical activity
RPE: Rating of Perceived Exertion
VR: virtual reality
WHO: World Health Organization

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Original Paper

Effects of a Modern Virtual Reality 3D Head-Mounted Display Exergame on Simulator Sickness and Immersion Under Specific Conditions in Young Women and Men: Experimental Study

Julia Ciążyńska[1], MSc; Michał Janowski[2], PhD Eng; Janusz Maciaszek[1], PhD

[1]Department of Physical Activity and Health Promotion Science, Poznan University of Physical Education, Poznan, Poland

[2]Department of Athletics, Strength and Conditioning, Poznan University of Physical Education, Poznan, Poland

Corresponding Author:
Julia Ciążyńska, MSc
Department of Physical Activity and Health Promotion Science
Poznan University of Physical Education
61-871 Poznan
Królowej Jadwigi 27/39
Poznan, 61-871
Poland
Phone: 48 (61) 835 52 14
Email: ciazynska@awf.poznan.pl

Abstract

Background: Many young adults do not reach the World Health Organization's minimum recommendations for the amount of weekly physical activity. The virtual reality 3D head-mounted display (VR 3D HMD) exergame is a technology that is more immersive than a typical exercise session. Our study considers gender differences in the experience of using VR games for increasing physical activity.

Objective: The aim of this study was to examine the differences in the effects of VR 3D HMD gaming in terms of immersion, simulator sickness, heart rate, breathing rate, and energy expenditure during two 30-minute sessions of playing an exergame of increasing intensity on males and females.

Methods: To examine the effects of the VR 3D HMD exergame, we experimented with 45 participants (23 males and 22 females) exercising with VR 3D HMD Oculus Quest 1, hand controllers, and Zephyr BioHarness 3.0. Players exercised according to the Audio Trip exergame. We evaluated the immersion levels and monitored the average heart rate, maximum heart rate, average breathing rate, maximum breathing rate, and energy expenditure in addition to simulator sickness during two 30-minute exergame sessions of increasing intensity.

Results: Audio Trip was well-tolerated, as there were no dropouts due to simulator sickness. Significant differences between genders were observed in the simulator sickness questionnaire for nausea ($F_{2,86}$=0.80; P=.046), oculomotor disorders ($F_{2,86}$=2.37; P=.010), disorientation ($F_{2,86}$=0.92; P=.040), and total of all these symptoms ($F_{2,86}$=3.33; P=.04). The measurements after the first 30-minute VR 3D HMD exergame session for all the participants showed no significant change compared to the measurements before the first 30-minute exergame session according to the total score. There were no gender differences in the immersion ($F_{1,43}$=0.02; P=.90), but the measurements after the second 30-minute exergame session showed an increase in the average points for immersion in women and men. The increase in the level of immersion in the female group was higher than that in the male group. A significant difference between genders was observed in the average breathing rate ($F_{2,86}$=1.44; P=.04), maximum breathing rate ($F_{2,86}$=1.15; P=.047), and energy expenditure ($F_{2,86}$=10.51; P=.001) measurements. No gender differences were observed in the average heart rate and maximum heart rate measurements in the two 30-minute sessions.

Conclusions: Our 30-minute VR 3D HMD exergame session does not cause simulator sickness and is a very immersive type of exercise for men and women users. This exergame allows reaching the minimum recommendations for the amount of weekly physical activity for adults. The second exergame session resulted in simulator sickness in both groups, more noticeably in women, as reflected in the responses in the simulator sickness questionnaire. The gender differences observed in the breathing rates and energy expenditure measurements can be helpful when programming VR exergame intensity in future research.

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KEYWORDS

virtual reality; HMD; simulator sickness; immersion; physical activity; exergame; Zephyr; gender differences; WHO recommendation; young adult; digital health; energy expenditure; exercise game

Introduction

Background

Several studies have shown evidence that excessive sedentary behavior can harm the health of people [1-4] and that programmed physical activity may increase health-related fitness [5,6]. According to the new recommendations of the World Health Organization, adults (18-64 years) should exercise for 150-300 minutes a week at moderate intensity or 75-150 minutes at vigorous intensity [7]. For moderate intensity activities, it is about 22-42 minutes of physical activity a day to improve health. Adults should also engage in a muscle-strengthening exercise of moderate or high intensity that engages all the major muscle groups for 2 or more days per week [7]. However, it should be emphasized that this is an absolute minimum that is often not achieved [8,9]. Studies have shown that young female adults typically engage lesser in physical activity than men [10], but both genders have difficulty achieving the World Health Organization recommendations for weekly physical activity [11]. Globally, in 2016, more than a quarter of all adults were not performing enough physical activity [11]. The world of computer devices is often blamed for low activity and a sedentary lifestyle [12], and the group at risk is people in their 20s and 30s because they are the most active gamers [13]. Over the past 2 decades, the number of female video game players has increased, and females today make up half of the gaming population [14]. The enthusiasm of young people should be channelized to play virtual reality (VR) games because of the positive enhanced heart rates and energy expenditure during exergames compared to those while playing on traditional computer displays [15]. In 2016, the VR games market began to develop dynamically, and the equipment used for VR gaming was modernized. Most studies until 2016 showed that women users experienced high simulator sickness and low immersion while using the same VR play equipment and content as men [16-20]. Males and females may be sensitive to different features of the simulated environment and may experience simulator sickness accordingly (females more for 2D environments, while males for 3D environments). Further, different studies have reported increased simulator sickness differences between men and women according to the type of the utilized head-mounted display (HMD) equipment and categories of VR content (female users experienced more discomfort compared to males when exposed to high emotional and arousing content). Recent studies have shown that proper modern equipment and properly selected game content can minimize the feelings of simulator sickness and increase immersion in both genders [21-24]. However, the previous studies do not refer to exergames based on programmed physical exercises in the VR 3D HMD. No study has shown VR exergaming as a form of physical activity that can be performed for fulfilling the weekly physical activity recommendations of the World Health Organization for adults. Immersive VR 3D HMD exergaming systems are plain body movements and are close to the planned, structured, and repetitive elements of a typical moderate training session [25]. Immersion is one of the main factors required for enabling the game users to perceive all aspects to create a real-life impression [16]. VR 3D HMD exergame is a technology that is more immersive than a typical exercise session [20]. An exergame that is a whole-body exercise is important, and it should involve rhythmic activity from large muscle masses, require quick shuffling to change positions, and should include locomotor tasks or even defensive actions to promote increased energy expenditure [26].

Goal of This Study

Our study presents a VR device as a tool to reach the minimum recommendations of the World Health Organization for the amount of weekly physical activity and to counteract a sedentary lifestyle. As per the World Health Organization recommendation, we divided the exergame sessions into two 30-minute sessions to assess whether the minimum recommendation could be achieved by both the genders. The 30-minute sessions have also been used in another HMD study [27] and has shown a positive response in the mental health of young adults. We chose individuals in the age group of 19-29 years as the most vulnerable to a sedentary lifestyle. The aim of this study was to evaluate the effects of a modern 3D HMD exergame on simulator sickness and immersion under specific conditions in healthy people. Thus, the risk of influence of other factors such as poor health, chronic diseases, and low endurance was reduced. In our experiment, we chose such conditions for playing the exergame to minimize gender differences, and we matched the game type for a group of recipients. We chose Oculus Quest 1 with Audio Trip, a first-person perspective game with 3D vision and a low emotional VR environment, for both genders. As the sessions increased in intensity, we collected data on the heart rate, breathing rate, and energy expenditure.

Hypotheses

We formed 3 hypotheses in this study.

1. Hypothesis 1: playing Audio Trip with a modern VR 3D HMD would result in higher cardiovascular function in men.
2. Hypothesis 2: playing Audio Trip with a modern VR 3D HMD would not cause simulator sickness in both genders.
3. Hypothesis 3: playing Audio Trip with a modern VR 3D HMD would have an immersion level that is gender independent, regardless of the playing time.

Methods

Participants

Sample size estimations were conducted using G*Power 3.1 (Axel Buchner). Sample size estimations were done for all

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analyses, and the final targeted sample size was selected such that the analysis requiring the largest number of participants can be adequately powered. Based on meta-analyses, we expect a medium effect size of Cohen *f*=.26. The sample size required to reach a level of significance of .05 with a power of .80 is 26 participants. By making 3 measurements considering gender and an assumed dropout rate of 25%, we needed to recruit 33 people to test our hypotheses. We evaluated all the participants who signed up; there was a total of 45 participants. All the participants completed this study. To be eligible for participation in this study, the individual had to be a physical education student, be between 19 and 29 years old, and have a good health condition (no neurological disorders, disability, mental disorders, psychotropic medicines, injuries, or fresh injuries), have a score of 10 or less on the Ruffier Squat Test scale, and have had no interactions with VR equipment or similar VR stimulation before. Individuals were invited to participate in the study through personal invitations and emails.

Technology

The VR Oculus Quest 64 GB system (Oculus Quest system software, Facebook Inc, released on May 21, 2019) was used as the immersive VR technology in this study. It consists of a wireless headset through which the VR environment can be viewed and played with 2 hand controllers that enable interaction with the VR environment. People wearing glasses could also take part in this study because a special overlay for glasses was applied. To ensure proper performance, the room size should be at least 2 meters × 2 meters. The VR Oculus Quest 64 GB has a display of 5.7 inches, resolution of 2880 pixels × 1600 pixels, reference resolution of 1440 pixels × 1600 pixels, organic light emitting diode display type, and refresh frequency of 72 Hz. The name of the game that was used was Audio Trip and was distributed from the Oculus Quest store app.

Instruments

Four methods were used for the usability evaluation: Audio Trip VR exergame, Simulator Sickness Questionnaire (SSQ), The Immersion Questionnaire, and BioHarness 3.0 measurements. One of the inclusion criteria for the study was the Ruffier Squat Test.

The purpose of the Audio Trip VR game (Andromeda Entertainment) [28] is to dance to the rhythm and immerse into the virtual musical and fitness environment. A player is obliged to follow the colored path by using their hands to catch 2 colored gems, smash drums, and dodge virtual barriers. In this study, players had to follow a special 30-minute playlist 2 times in the beginner and regular modes. A playlist is a proprietary idea in which the beats per minute increase during play, and the difficulty level increases in the second session, thereby increasing the intensity. The details of the playlist are shown in Figure 1.

The SSQ is one of the most frequently used simulator testing tools [29]. In this research, we used the SSQ by Kennedy et al [30], translated into Polish by Biernacki et al [31]. One of the essential aspects of research on simulators is how different test conditions affect the severity of the symptoms due to a simulator. Among the conditions in this study, one should specify both the movement of the platform and the type of visual stimuli. This questionnaire evaluates 26 symptoms due to the simulator. Questions on nausea (question numbers 1, 8, 10, 11, 12, 22, 25), oculomotor disorders (question numbers 1, 2, 5, 6, 7, 12, 15), and disorientation (question numbers 7, 1, 14, 15, 16, 17, 18) were asked in the questionnaire. The task of the person examined using SSQ consists of making a subjective assessment of the severity of specific symptoms. A 4-step scale was used: (1) none, no symptoms due to the simulator; (2) small, few symptoms due to the simulator; (3) moderate, moderate symptoms due to the simulator; and (4) significant, serious symptoms due to the simulator. The SSQ result includes both the overall levels of the symptoms from using a simulator (SSQ total), and the indicators consist of individual (unportioned relative to each other) scales: (1) nausea symptoms of increased salivation, sweating, nauseousness, and burping; (2) oculomotor disorder symptoms of fatigue, headache, eye fatigue, and difficulty in concentration; and (3) disorientation symptoms of dizziness, daze feeling (both with open and closed eyes), and blurriness (out of focus). The first step when calculating SSQ is to convert the results to a numerical form. The SSQ scales are expressed on a 4-stage Likert scale (where 0=none, 1=small, 2=moderate, and 3=significant). For calculating the score for SSQ, add raw values for the data of the symptoms assigned to the specified factor and multiply by a specific number. For individual scales, they are as follows: (1) nausea, 9.54 (score ranging from 0 to 200.34); (2) oculomotor disorders, 7.58 (scores ranging from 0 to 159.18); (3) disorientation, 13.92 (scores ranging from 0 to 292.32); and (4) SSQ total, 3.74 (scores ranging from 0 to 235.62).

The Immersion Questionnaire is a scale measuring video game engagement [32]. In this research, we used the Immersion Questionnaire by Jennett et al [32], which was translated into Polish by Strojny et al [33]. This questionnaire was used as a tool for measuring the player's absorption/immersion while playing games. Researchers commonly consider immersion to be an important part of the videogame user experience [34-37]. The Polish adaptation consists of 27 test items instead of 31 questions of the original questionnaire, because 4 questions in the original questionnaire had a low correlation with the overall test score and are unnecessary [38]. The Immersion Questionnaire scales are expressed on a 5-stage Likert scale (where 1=very small, 2=small, 3=average, 4=more than average, 5=a lot/definitely). The total score to earn on the Immersion Questionnaire is 135.

A portable wireless piezoelectric recording system (BioHarness 3.0, OmniSense 3.9.7, Zephyr Technology Corp) [39] was used for monitoring energy expenditure, estimated according to the following formula: energy expenditure (kcal) = gender × (–55.0969 + 0.6309 heart rate + 0.1988 weight + 0.2017 age) + (1 – gender) × (–20.4022 + 0.4472 heart rate – 0.1263 weight + 0.074 age) (gender: 1 for male, 0 for female; heart rate, including average heart rate and maximum heart rate; and breathing rate, including average breathing rate and maximum breathing rate).

In the Ruffier Squat Test, participants are made to do 30 squats in 45 seconds [40]. Heart rate is recorded before the test (P1), at the end of 45 seconds (P2), and at 1 minute after the test (P3).

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The test score is calculated in the form of an index—the Ruffier Index expressed as (P1 + P2 + P3) – 200/10. The range of the Ruffier Index given was 0 to 17, but higher than 10 is an adaptation to insufficient effort or even poor adaptation. The individual ranges are as follows: 0 is a very good adaptation to effort, between 0 and 5 is a good adaptation to effort, and between 5 and 10 (including 10) is the ability to adapt to the average effort. Ruffier originally developed this test for testing the European population.

Figure 1. Exergame playlist in beginner and regular modes of the Audio Trip virtual reality game, including the title, duration of songs, and beats per minute. BPM: beats per minute.

TITLE (chronological)	DURATION (min:sec)	BPM (beats per minute)
DANCE MONKEY	03:28	98
BANGARANG	03:32	110
JUST DANCE	03:38	118
KRISHNA	02:39	128
RED	07:31	136
SATISFACTION	04:44	136
MANDALA	04:39	143

Procedure

Each participant came once to be examined and approved for research and to take part in the main study. Each participant attended an information meeting. They were informed of the study and encouraged to ask questions, after which they signed a written consent form if they agreed to participate. The study protocol is presented in a chronological order in Figure 2. The participants filled in the first 2 pages of SSQ (see Multimedia Appendix 1). The first page included preliminary information before starting the study about simulator experience and physical statements, that is, level of current physical fitness, the occurrence of diseases during a week, alcohol consumption, medications taken 24 hours before the study, and sleep duration. The second page collected information on cybersickness data before the first 30-minute VR 3D HMD exergame session. Before completing the SSQ, a BioHarness 3.0 sensor was attached to the chest by a strap and calibrated with a computer. The participants were weighed and their heights were measured, and then these data were entered into the OmniSense software (Zephyr BioHarness 3.0).

Each participant took part in a 5-minute warm-up, according to the instructions in a video prepared earlier (see Figure 3). The VR 3D exergame tutorial starts with the calibration of HMD and controllers. People wearing glasses could also take part in this study because a special overlay for glasses was applied. Moreover, left-handed people could take part in this study. The participants stood next to an imaginary console with songs and were then fitted with the VR equipment. At this point, researchers had a preview of the VR world on the screen of the mobile phone to be able to see what the participant saw during the experimental sessions. The safe space for the participant to move was a square of 2.5 meters × 2.5 meters. In the VR environment, the controllers were represented by hands in the console environment and by 2-color orbs in the exergame environment. The tutorial was built in steps, with each step being supported by instructions on what tasks to perform to meet the goal to proceed to the next step, and the tasks were graded from the easiest to the most difficult (see Multimedia Appendix 2). The details of the playlist are shown in Figure 1. The intensity of the game increases during each session and with the difficulty level. The participants were dressed in casual sports clothes (Figure 4) and had safety face pads between the HMD Oculus Quest headset and their face. The details on what the Audio Trip game looks like are shown in Figure 5. We determined whether a participant managed to perform each task by noting the points for every 7 songs from a playlist on the checklist box. Between the songs was a quick pause to select the next one from the playlist.

After the first 30 minutes of the exergame playlist session, participants proceeded to the measurements that were taken between the 2 sessions: The Immersion Questionnaire, SSQ, and BioHarness 3.0 measurements (Figure 2). The participants were expected to answer the questions alone, but some questions required clarification and affirmation by the researcher to confirm the proper interpretation. After completing the measurements in the interval between the 2 sessions, the second session of the exergame started. The interval time of 15-20 minutes was enough for the heart rates of all the participants to return to normal resting heart rate before the start of the next game session. The game was then launched on the regular level. After completing the second 30-minute playlist (60 minutes in total), the same measurements were performed as done between the 2 sessions.

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Figure 2. Study protocol presented in the chronological order from left to right for the experimental group. Br-Ave: average breathing rate; Br-Max: maximum breathing rate; EE: energy expenditure; HR-ave: average heart rate; HR-Max: maximum heart rate; SSQ: Simulator Sickness Questionnaire; TIQ: The Immersion Questionnaire; VR: virtual reality; ZB3: Zephyr Bioharness 3.0.

duration:	20 min	15-20 min	30 min	15-20 min	30 min	15-20 min
Experimental group (N=45)	**PREPARATION**	**PRE** (before first session)	**FIRST 30-MIN SESSION**	**INTER** (between sessions)	**SECOND 30-MIN SESSION**	**POST** (after second session)
	Inclusion criteria check	SSQ	BEGINNER MODE	TIQ	REGULAR MODE (higher intensity)	TIQ
	ZB3 calibration	ZB3	ZB3: HR-Max, HR-Ave, BR-Max, Br-Ave, EE	SSQ	ZB3: HR-Max, HR-Ave, BR-Max, Br-Ave, EE	SSQ
		Warm-up		ZB3		ZB3
		VR calibration				

Figure 3. The various elements of the 5-minute warm-up (5: running in place, 4: arm swings, 3: torso twists, 2: torso bends, 1: warming the joints, that is, wrist and ankle) on the television.

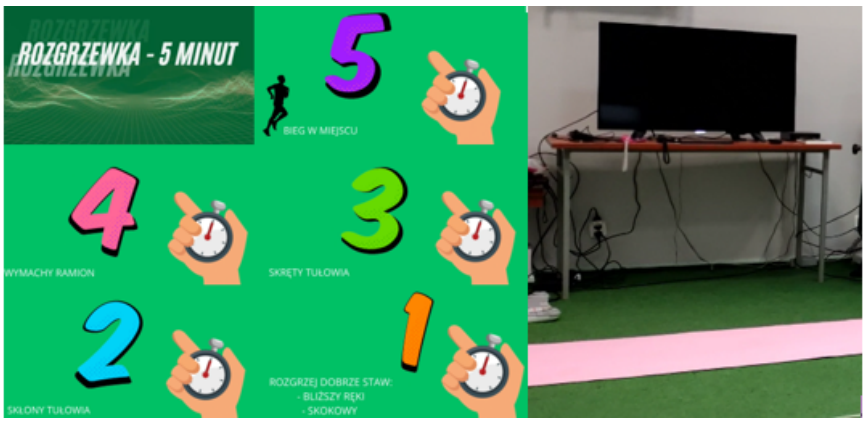

Figure 4. Virtual reality exergame intervention in a safe area of 2.5 meters × 2.5 meters.

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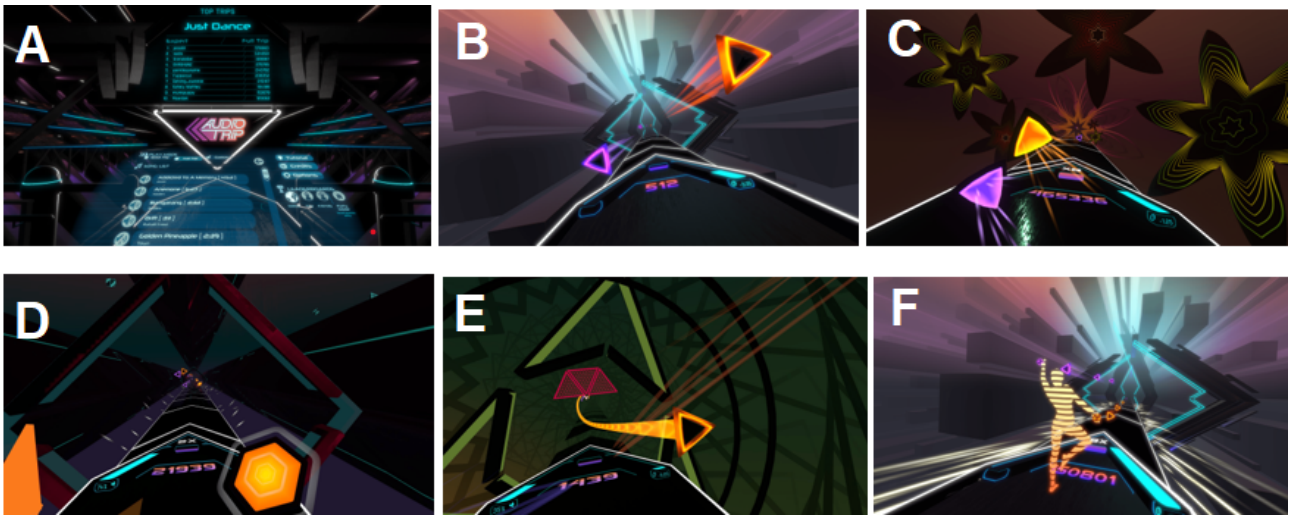
Figure 5. View of the Audio Trip game. From left: A. Selecting a track from the list.; To the rhythm of the music, hitting two-colored triangles as intended: B. touching by R/L hand C. hitting at a certain angle by R/L hand, D. smashing the drums by R/L hand, E. following the path by R/L hand and dodging the barriers.; F. Following the trainer (back perspective).



Data Interpretation

We analyzed the data measured from BioHarness 3.0 in the experiment by using the OmniSense software. The data measured from the experiment are maximum heart rate, average heart rate, maximum breathing rate, average breathing rate, and energy expenditure. Repeated-measures analysis of variance (ANOVA) was used to test the hypotheses. We analyzed the data using Statistica 13.3 (TIBCO Software Inc), and statistical significance was defined as $P \leq .05$.

Ethics Approval

This study was performed according to the ethical standards laid down in the Declaration of Helsinki. All participants provided signed informed consent, and the Bioethics Commission of Poznan University of Medical Sciences granted the ethical approval for this study (decision 32/20).

Results

Participant Characteristics

The mean age (in years) of the participants (N=45) was 21.69 (SD 2.76; range 19-28). The mean body weight (in kilograms) was 71.03 (SD 13.07; range 44.5-106.5). The mean body height (in centimeters) was 173.98 (SD 8.09; range 155.6-186.1). The mean body mass index (in kg/m²) was 23.3 (SD 3.23; range 18.4-32.3). The experimental group was mixed; females constituted 49% (22/45) of the study population (Table 1).

Table 1. Characteristics of the study population (N=45).

Participant characteristic	Value
Mean age (years)	21.69
Mean body weight (kg)	71.03
Mean body height (cm)	173.98
Mean BMI (kg/m²)	23.3
Females (n)	22
Ruffier index	6.5

SSQ Results

Nausea

Significant differences between genders were observed in nausea symptoms (Table 2), that is, increased salivation, sweating, nauseousness, and burping. Analysis of the results with the ANOVA test showed that the size of the changes in the mean values for the SSQ nausea score was $F_{2,86}=0.80$ ($P=.46$).

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Table 2. Gender differences in nausea during the 3 measurements.[a]

Simulator sickness questionnaire on nausea	Female group	Male group
Before the first 30-minute exergame session		
Average (SD)	9.54 (9.74)	10.37 (9.22)
Minimum points	0	0
Maximum points	28.62	38.16
Between the exergame sessions		
Average (SD)	13.01 (10.54)	18.25 (11.19)
Minimum points	0	0
Maximum points	38.16	47.7
After the second 30-minute exergame session		
Average (SD)	20.38 (13.05)	22.40 (12.87)
Minimum points	0	0
Maximum points	57.24	47.7

[a]$F_{2,86}$=0.80; P=.046.

Oculomotor Disorders

Significant differences between genders were observed in oculomotor disorder symptoms (Table 3), that is, fatigue, headache, eye fatigue, and difficulty in concentrating. Analysis of the results with the ANOVA test showed that the size of the changes in the mean values for the SSQ oculomotor disorders score was $F_{2,86}$=2.37 (P=.10).

Table 3. Gender differences in the simulator sickness questionnaire for oculomotor disorders during the 3 measurements.[a]

Simulator sickness questionnaire on oculomotor disorders	Female group	Male group
Before the first 30-minute exergame session		
Average (SD)	18.26 (14.18)	14.50 (12.25)
Minimum points	0	0
Maximum points	60.64	30.32
Between the exergame sessions		
Average (SD)	22.74 (13.32)	11.21 (14.01)
Minimum points	0	0
Maximum points	53.06	30.32
After the second 30-minute exergame session		
Average (SD)	34.11 (18.80)	21.09 (15.33)
Minimum points	0	0
Maximum points	83.38	53.06

[a]$F_{2,86}$=2.37; P=.010

Disorientation

Significant differences between genders were observed in disorientation symptoms (Table 4), that is, dizziness, daze feeling (both with open and closed eyes), and blurriness (out of focus). Analysis of the results with the ANOVA test showed that the size of the changes in the mean values for the SSQ disorientation score was $F_{2,86}$=0.92 (P=.40).

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Table 4. Gender differences in the simulator sickness questionnaire on disorientation during the 3 measurements.[a]

Simulator sickness questionnaire on disorientation	Female group	Male group
Before the first 30-minute exergame session		
Average (SD)	11.39 (11.42)	7.87 (10.05)
Minimum points	0	0
Maximum points	41.76	27.84
Between the exergame sessions		
Average (SD)	16.45 (15.67)	5.45 (7.49)
Minimum points	0	0
Maximum points	55.68	55.68
After the second 30-minute exergame session		
Average (SD)	24.68 (22.80)	15.13 (10.65)
Minimum points	0	0
Maximum points	69.60	83.52

[a]$F_{2,86}$=0.92; P=.004.

SSQ Total Symptoms

Audio Trip was well-tolerated, as there were no dropouts due to simulator sickness. Significant differences between genders were observed in SSQ total symptoms (oculomotor disorders + nausea + disorientation). Analysis of the results with the ANOVA test showed the size of changes in mean values for the SSQ total symptoms was $F_{2,86}$=3.33 (P=.04); however, after the first 30-minute session, all participants showed no significant change compared to premeasurements according to SSQ total symptoms results (Table 5 and Figure 6). One-way ANOVA showed no significant differences between the measurements for men (P=.83) and women (P=.59) before the first 30-minute exergame session and between the sessions.

The two 30-minute sessions of the exergame changed the SSQ profile only in the male group. The SSQ profile of males changed during the 3 measurements as follows (highest score to the smallest score): oculomotor disorders>nausea>disorientation before the first session, nausea>oculomotor disorders>disorientation between the 2 sessions, and nausea>oculomotor disorders>disorientation after the second session. However, the SSQ profile of the female group remained the same in every measurement, that is, before, between, and after the exergame sessions, as follows: oculomotor disorders>disorientation>nausea. The mean points for the SSQ profiles are described in Table 6.

Table 5. Gender differences in the simulator sickness questionnaire for the total symptoms during the 3 measurements.[a]

Simulator sickness questionnaire on the total symptoms	Female group	Male group
Before the first 30-minute exergame session		
Average (SD)	15.47 (11.41)	13.65 (10.68)
Minimum points	0	0
Maximum points	48.62	33.66
Between the exergame sessions		
Average (SD)	21.93 (11.55)	13.01 (9.22)
Minimum points	0	0
Maximum points	52.36	33.66
After the second 30-minute exergame session		
Average (SD)	32.98 (17.30)	15.13 (16.60)
Minimum points	0	0
Maximum points	74.80	59.84

[a]$F_{2,86}$=3.33; P=.04.

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Figure 6. Gender differences in the total simulator sickness score during the three measurements. PRE: before the first 30-minute exergame session; INTER: between the exergame sessions; POST: after the second 30-minute exergame session; SSQ: Simulator Sickness Questionnaire.

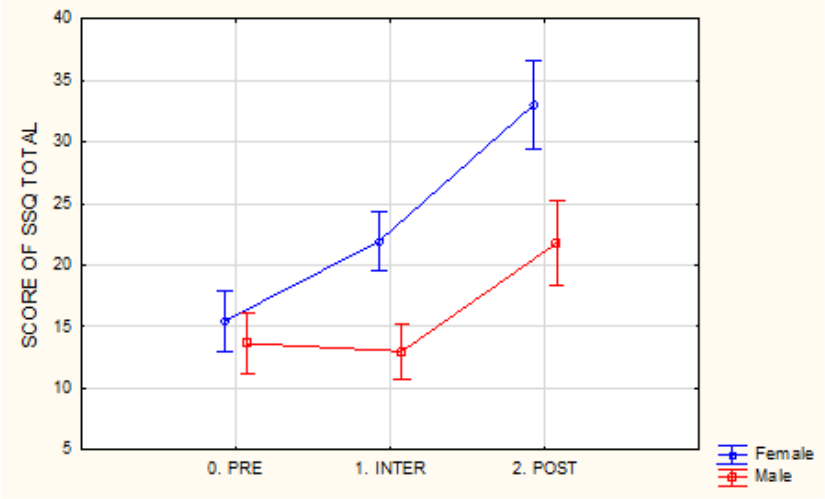

Table 6. Gender differences for the simulator sickness questionnaire profile during the 3 measurements.

Simulator sickness questionnaire profile	Female group	Male group
Before the first 30-minute exergame session (mean points)		
Oculomotor disorder	18.26	14.50
Nausea	9.54	10.37
Disorientation	11.39	7.87
Between the exergame sessions (mean points)		
Oculomotor disorder	22.74	11.21
Nausea	13.01	18.25
Disorientation	16.45	5.45
After the second 30-minute exergame session (mean points)		
Oculomotor disorder	34.11	21.09
Nausea	20.38	22.40
Disorientation	24.68	15.13

The Immersion Questionnaire

No significant differences between genders were observed in the Immersion Questionnaire score (Table 7 and Figure 7). Analysis of the results with the ANOVA test shows the size of changes in the mean values for the Immersion Questionnaire score ($F_{1,43}$=0.02; P=.89).

Table 7. Gender differences in the immersion questionnaire during the 2 measurements.[a]

Immersion questionnaire	Female group	Male group
Between the exergame sessions		
Average (SD)	106.23 (7.80)	103.04 (10.68)
Minimum points	72	78
Maximum points	121	121
After the second 30-minute exergame session		
Average (SD)	110.05 (11.06)	106.56 (10.83)
Minimum points	79	76
Maximum points	129	129

[a]$F_{1,43}$=0.02; P=.89

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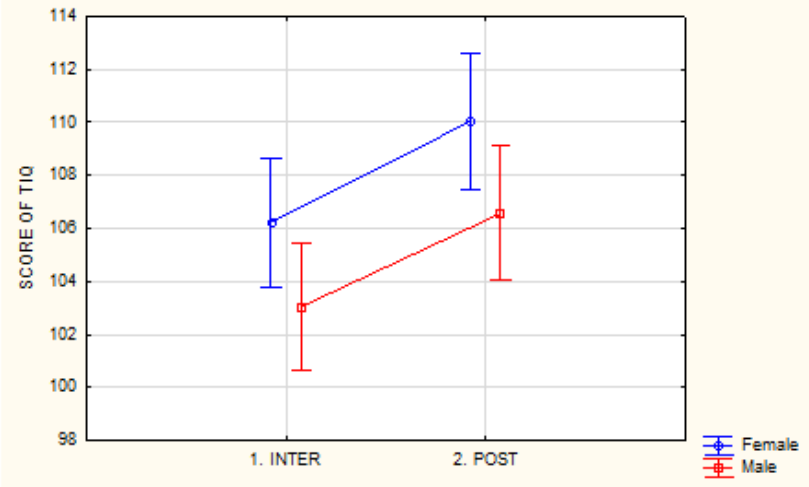
Figure 7. Gender differences in the immersion questionnaire score during the two measurements. INTER: between the exergame sessions; POST: after the second 30-minute exergame session; TIQ: The Immersion Questionnaire.



BioHarness Measurements

A significant gender difference was observed in the average breathing rate ($F_{2,86}$=1.44; P=.04), maximum breathing rate ($F_{2,86}$=1.15; P=.047), and energy expenditure ($F_{2,86}$=10.513; P=.001) measurements (Table 8). No gender differences appeared in the average heart rate and maximum heart rate measurements in the two 30-minute sessions.

Table 8. Gender differences in the average heart rate, maximum heart rate, average breathing rate, maximum breathing rate, and energy expenditure during the 3 measurements.

BioHarness measurements	Female group	Male group	Interaction, *F* test *(df)*	*P* value
Average heart rate			0.19 (2,86)	.83
Before the first 30-minute exergame session	90.95	80.87		
Between the exergame sessions	142.72	129.86		
After the second 30-minute exergame session	144.68	133.56		
Maximum heart rate			0.29 (2,86)	.75
Before the first 30-minute exergame session	110.77	101.26		
Between the exergame sessions	171.82	158.17		
After the second 30-minute exergame session	172.77	160.52		
Average breathing rate			1.44 (2,86)	.04
Before the first 30-minute exergame session	14.50	12.91		
Between the exergame sessions	27.95	28.99		
After the second 30-minute exergame session	27.05	28.70		
Maximum breathing rate			1.15 (2,86)	.047
Before the first 30-minute exergame session	23.09	21.65		
Between the exergame sessions	37.27	35.04		
After the second 30-minute exergame session	36.27	36.65		
Energy expenditure			10.513 (2,86)	.001
Before the first 30-minute exergame session	33.82	39.47		
Between the exergame sessions	267.95	340.96		
After the second 30-minute exergame session	272.77	356.82		

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Discussion

Principal Findings

Hypothesis 1: Audio Trip Exergame With Modern VR 3D HMD Would Result in Higher Cardiovascular Function in Men

The findings from this study provide support for our first hypothesis. A significant gender difference was observed in the average breathing rate ($F_{2,86}$=1.44; P=.04), maximum breathing rate ($F_{2,86}$=1.15; P=.047), and energy expenditure ($F_{2,86}$=10.513; P=.001) measurements. Seebauer et al [41] suggested that the effect of exercise intensity on the occurrence of coordination between breathing rate and rhythms of exercise differs between men and women. A similar mechanism could have occurred in our study due to the use of a rhythmic music game. During heavy exercise, tidal volume plateaus and increase in minute ventilation can only be reached via an increase in the breathing rates and energy expenditure. Interestingly, even though women have smaller lung volumes compared to men [42], in our study, men adjusted their breathing rates more during the whole exergame session. Trinschek et al [43] proved that men showed significantly higher values in cardiorespiratory variables (by 12%-34%) during the running treadmill test until exhaustion [43]. Men users feel more excited when they do something they like very much or want to achieve something and are forced to breathe more frequently during an exercise session [44]. Additionally, the frequency of breathing increases energy expenditure [45]. Breathing can also change in response to changes in emotions. Due to the physical activity, the attractiveness of the task, perceived competence, and autonomy concerning emotional experience are especially important aspects [46]. Although our study showed a prominent level of immersion, it can be assumed that satisfaction influenced the need to increase breathing in male users. The values of average heart rate and maximum heart rate showed no gender differences in both sessions because the groups were well-matched in terms of physical performance, as per the Ruffier Squat Test inclusion criterion in this study.

Hypothesis 2: Audio Trip Exergame With Modern VR 3D HMD Will Not Cause Simulator Sickness in Both Genders

The findings from our study provide partial support for our second hypothesis. There were statistical differences between the genders in both sessions: men were more resistant to simulator sickness than women. After two 30-minute sessions, there was a change in simulator sickness ($F_{2,86}$=3.33; P=.04); however, after the first 30-minute session, all participants showed no significant change compared to premeasurements according to SSQ total results. Although there is a lack of studies about gender imbalance in the susceptibility to simulator sickness in the context of modern HMDs, some studies do elucidate this point [23,24,47]. Female participants may experience discomfort only in specific conditions (movements in first-person perspective). Males and females may be sensitive to different features of the simulated environment and experience simulator sickness accordingly (females more for 2D environments, while males for 3D). Studies have shown the causes for simulator sickness in men and women, which are different by the type of the utilized HMD equipment and categories of VR content (female participants experienced more discomfort compared to males when exposed to highly emotional and arousing content) [22]. A systematic review on gender differences in VR HMD [23] showed that women are commonly more sensitive to simulator sickness when the realism of the content is low or when the game is highly emotional. Such an increase in SSQ total score in women can be partially explained that female users may be more willing to report distress and discomfort during the experiment [48]. This may be due to the social biological differences and social expectations [49]. The newest HMD technology can provide a more advantageous experience [27,50] and if this is combined with a careful selection of VR content, the risk of VR simulator sickness can be leveled off. Furthermore, Giammarco et al [51] suggested that gender differences in SSQ scores may be differentially related to gender differences in cognitive functions like spatial attention depending on the VR environment. Another aspect is that the VR HMD simulator sickness has been found to increase after 10 minutes [52]. Our study showed that only the second session (a total of 60 minutes of VR exergaming) of VR content caused statistically significant differences in simulator sickness. Therefore, the hypothesis was confirmed partially, because only the first 30-minute of the Audio Trip exergame will not cause simulator sickness in adults, which is a positive finding in the field of SSQ. A new type of VR HMD and appropriately selected content and intensity can help delay the appearance of the effects of simulator sickness for men and women, as shown in other VR studies [50,53]. Szpak et al [53] suggested that the exposure duration did not influence any visual measure, and observable changes in accommodation and vergence did occur within the first 10 minutes of VR exposure and did not significantly change for exposures up to 50 minutes. The results of our study should encourage men and women to try VR HMD exercise, without fearing that playing may have a high probability of causing them discomfort during 30 minutes of exergaming. The development of VR equipment and more modern games in the future should extend the effect of non–simulator sickness.

Hypothesis 3: Immersion Level is Gender Independent Regardless of the Playing Time

The findings from this study provide support for our third hypothesis. There were no gender differences in the level of immersion ($F_{1,43}$=0.02; P=.90) but the second 30-minute session showed an increase in the average points for both women and men. The increase in the level of immersion in the female group was higher than that in the male group. As we mentioned, immersion is one of the main factors required to enable the game users to perceive all aspects to create a real-life impression [16]. Studies until 2011 show that men are more frequent immersive users of VR devices. Men, regardless of their prior game experience, expressed more sensory immersion and more control over the environment than women. The golden period of VR was the year 2016. Since 2016, VR devices were contemporary and were found to be suitable for users (weightless, wireless, etc). Our study suggests that there are no

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gender differences concerning the level of immersion with contemporary VR equipment (Oculus Quest) if the VR content is suitable for both genders. Our experiment was performed with physical education students who had not interacted with VR equipment or similar VR stimulation before, and we made sure that the content of the game was interesting for both genders (physical exercise for physical education students). Physical exergame content (Audio Trip) and technical capabilities (wireless HMD, hand controllers) can probably contribute to the reduction of gender differences.

Limitations

The first limitation in this study was the assessment of the breathing rate based on chest movements alone. Based upon the principle of a strain gauge sensor, thoracic expansion and contraction cause size differentials that induce changes in capacitance because of the resultant changes in impedance. The change in impedance is manifested as a change in the waveform signal amplitude represented as a sine wave with downward and upward deflections, indicating chest expansion (increased impedance) and contraction (decreased impedance), respectively [54]. Incorrect tension on the chest strap may prevent adequate sensor response to chest expansion and contraction [39]. To eliminate the effects of these variances, we recommend the use of additional tools such as spirometry for future studies measuring physiological effort and energy expenditure.

The second limitation in this study was the acceptance of the necessity to be a physical education student as one of the inclusion criteria in this study. The aim was to study the effects the VR 3D HMD exergame on fully healthy and fit people. This allowed reducing the risk of the influence of other factors, for example, poor health, chronic diseases, and low endurance. In addition, what we tried to highlight in our study, which mattered the most, was the interest in the type of game and the gathering of the appropriate number of people for research who would meet the inclusion criteria, including the Ruffier Squat Test score. We chose people interested in sports by the type of studies selected (physical education students).

Conclusions

This study showed that a 30-minute session of the VR 3D HMD exergame does not cause simulator sickness and is a very immersive type of exercise for men and women users. This exergame gives the opportunity to reach the minimum recommendations for the amount of weekly physical activity for adults. The second exergame session resulted in simulator sickness in both groups, more noticeably in women, as indicated by the responses in the SSQ. Gender differences were observed in the breathing rate and energy expenditure measurements, and this information can be helpful when programming VR exergame intensities in future research. Our findings provide a foundation for future research on VR exergames with no simulator sickness but as a refreshing and an enjoyable type of exercise for male and female users. Motivating the public to be physically active is perhaps one of the most important and difficult tasks. Gamification of physical exercises can facilitate more weekly physical activity than that recommended by the World Health Organization for minimum weekly physical activity for adults. Future immersive exergaming concepts should focus on increasing the intensity while considering user susceptibility to simulator sickness.

Authors' Contributions

JC conducted the experimental procedure; wrote the manuscript; provided data for Tables 1-7, Figures 1-7, multimedia appendices, and TOC image; and conducted all the statistical analyses. MJ provided data for Table 8. JC, MJ, and JM reviewed the final manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1
The simulator sickness questionnaire.
[DOCX File , 244 KB - games_v10i4e41234_app1.docx]

Multimedia Appendix 2
Audio Trip virtual reality tutorial video.
[MP4 File (MP4 Video), 19379 KB - games_v10i4e41234_app2.mp4]

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Abbreviations

ANOVA: analysis of variance
HMD: head-mounted display
SSQ: Simulator Sickness Questionnaire
VR: virtual reality

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Original Paper

Applying Gamification Principles and Therapeutic Movement Sequences to Design an Interactive Physical Activity Game: Development Study

Hyungsook Kim[1,2,3], PhD; David Michael O'Sullivan[4], PhD; Seong Hee Chung[3], MSc

[1]Department of Cognitive Sciences, Hanyang University, Fusion Technology Center, Seoul, Republic of Korea
[2]Graduate School of Public Policy, Hanyang University, Seoul, Republic of Korea
[3]Hanyang Digital Healthcare Center, Hanyang University, Seoul, Republic of Korea
[4]Division of Sport Science, Pusan National University, Pusan, Republic of Korea

Corresponding Author:
David Michael O'Sullivan, PhD
Division of Sport Science
Pusan National University
2, Busandaehak-ro 63beon-gil, Geumjeong-gu
Pusan, 46241
Republic of Korea
Phone: 82 1076845811
Fax: 82 5105103746
Email: davidosullivan@pusan.ac.kr

Abstract

Background: Depression is a severe illness that has accelerated with the spread of COVID-19 and associated lockdowns. As a result, reported physical activity has substantially decreased, further increasing depressive symptoms.

Objective: This study aims to explain the use of gamification principles to develop content for an interactive physical activity game for depression based on clinically proven depression diagnostic criteria.

Methods: We discuss related work in this field, the game design framework, the users' depression severity, how we customize the contents accordingly, the gradual progression of the game to match exercise principles, and user flow optimization.

Results: We provide a brief description of each of the games developed, including instructions on how to play and design aspects for flow, audio, and visual feedback methods. Exergames (interactive physical activity–based games) stimulate certain physical fitness factors such as improving reaction time, endurance, cardiovascular fitness, and flexibility. In addition, the game difficulty progresses based on various factors, such as the user's performance for successful completion, reaction time, movement speed, and stimulated larger joint range of motions. Cognitive aspects are included, as the user has to memorize particular movement sequences.

Conclusions: Mental health issues are linked to behavior and movement; therefore, future physical activity–based interactive games may provide excellent stimulation for inducing user flow, while physical activity can help train various physical fitness factors linked to depression.

(JMIR Serious Games 2022;10(4):e38133) doi:10.2196/38133

KEYWORDS

home workout; mobile assistant; movement; physical activity; depression

Introduction

The adverse effects of the COVID-19 pandemic have substantially affected the physical and mental health of the public worldwide [1,2]. Lockdowns and restrictions have resulted in an increase in the lack of physical activity and depression [3,4]. Health care providers are responsible for addressing these issues. Until recently, exercise was a prominent nonpharmaceutical therapeutic method to supplement pharmacology and additional invasive treatments for mental health issues. Exercise has been shown to be effective in ameliorating mental health–related issues such as depression

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[5,6] and dementia [7,8]. Despite the significant effectiveness of exercise as a complementary method to improve the symptoms of mental health issues, it is challenging for people to remain engaged in and motivated to continue exercising [9,10]. Therefore, it is vital to provide users with physical activity–based immersive and fun interventions to optimize retention. Furthermore, a vast amount of research indicates that even minimal increases in physical activity lead to highly significant improvements in the health status of the general population [11,12]. Research shows a dose-response relationship between an increase in physical activity and health-related benefits.

Gamification is a well-known process that increases fun, motivation, engagement, and flow during an activity. Its principles have been used in various areas to stimulate more immersive interactions during activities. Gamification is a proven method that can help increase physical activity, with many mobile apps and video game–based physical activity intervention products having their effectiveness proven through many studies [13-16]. Recent studies classify the types of gamification [17] into competition and cooperation, self-goal, storytelling type, and positive/negative reinforcement [18]. Competition, which provides incentives to increase physical activity, was reported to be the most effective method, and the gamification factor of support or collaboration did not significantly increase physical activity [16]. An additional essential element of gamification is aesthetics, with realistic graphic visual and sound effects that provide more fun to users by creating aesthetically pleasing environments with sensory stimulation. Reinforcement and rewards are reported to increase the level of immersion of game users, increase voluntary participation motivation, and increase the frequency and time of intervention participation [19-22]. In video game interventional therapy, high interactivity and better visual and auditory stimulation have been reported to ameliorate therapeutic effects [23]. In addition, among depression-related software in which gamification is applied, more than 16 apps have demonstrated direct therapeutic effects on depression in clinical research [24].

To develop our game, the movement sequence was designed to include various movement patterns for each body part, especially the arms, legs, and torso. The contents we developed provide a structure to stimulate the progression from basic motion to movement, that is, a sequence of motions. When the user performs (experiences) the game, a simple motion is repeated that strengthens the muscles surrounding the involved limbs. Tai-Chi–related research [25] shows that repetitive lifting of bodyweight and isometric movements (maintaining a static pose) can strengthen muscles and improve cardiovascular endurance. In addition, as exergames use bodyweight only, the level of movement intensity is similar to that of Tai-chi (where a practitioner moves through a series of poses). Therefore, we expect a similar physiological response in muscle strength and cardiovascular enhancement with only nonintense movements in the upper and lower limbs [24,26].

Furthermore, we expect that repeated movement patterns, especially in an open and upright posture in the vertical plane, can help improve the user's mood [27,28], reduce fatigue, and help improve focus for people with mild-to-moderate depression [29]. Movements with large ranges of each joint (ie, open or space-consuming posture) are defined as high power or powerful poses. This expansive, open pose (also called "power posing") is a method of nonverbal communication that improves not only the psychological state but also the neurohormones [30-32]. A user's positive experience reinforces the fun of participating and retains positive feedback in their memory. We also expect the positive effects of the regular use of this exergame to help increase users' daily physical activity levels due to improved physical function, cardiovascular fitness, and muscle strength.

Exergames, which are the innovation of using technology to stimulate exercise, show that gamification can help participants engage and enjoy exercise more. In particular, exergames are found to be effective for youth with obesity than for the older population with dementia [33]. In a systematic review, exergames have been shown to reduce depression symptoms, but their effectiveness depends on depression severity, the number of sessions, and game type (high and low playfulness) [24]. Although exergames have been shown to help increase the fun of exercise, to our knowledge, no exergames have been developed for the treatment and management of depression. Therefore, in this study, the objective was to explain how we used gamification principles to develop the contents of an exergame (interactive physical activity game) controlled by Azure Kinect (Microsoft Corporation) for depression based on clinically proven depression diagnostic criteria.

Methods

The Physical Activity Game Design Framework

A total of 6 diagnostic criteria (Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition [DSM-5]) and 6 core fitness factors (10-item Center for the Epidemiological Studies of Depression Short Form [CES-D-10]) were selected (details in Figure 1) through a review of the DSM-5 depression diagnostic criteria and the CES-D-10. We developed exergames with 6 different physical activities based on these 6 core fitness factors (coordination, cardiovascular endurance, balance, reaction time, muscular endurance, and agility).

The general procedure for mapping the 6 core factors when developing a game for each of them is as follows: First, the behavioral characteristics of the daily life of patients with depression were derived for each core factor. The specific behaviors of people with depression (depressive trait behaviors) were derived from these core factors and summarized through a literature review and detailed consultations with neurologists and mental health specialists. The core factors were then linked to fitness factors through a series of consultations with psychiatric clinicians and physical activity experts (Figure 2). Second, specific movement patterns that could strengthen each fitness factor linked to depressive behaviors were designed.

In this section, the theory and principles for developing the exergames are explained. The first step in game development was to extract the related fitness factors from the DSM-5 diagnostic criteria and the CES-10-D scale for depression. Then, specific exergames were developed based on the fitness factors

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needed to be trained. For example, the participants were required to follow the correct postures with their upper and lower bodies for coordination training, as demonstrated in the game.

Figure 1. Extraction of the 6 core fitness factors to stimulate the resulting physical activity characteristic of the CES-10-D questionnaire. CES-D-10: 10-item Center for the Epidemiological Studies of Depression Short Form.

No.	CES-10-D questions	Resulting physical activity characteristic	Objective physical movement by game stimulation	Critical fitness factor
1	I was bothered by things that usually don't bother me.	Slow	Fast	Power & speed
2	I felt depressed.	Closed posture (minimal movement)	Stretching	Flexibility
3	I felt that everything I did was an effort.	Lack of strength (lack of energy)	Strengthen muscles	Strength & endurance
4	My sleep was restless.	Low cardiovascular endurance (lack of energy)	Increase cardiovascular fitness	Cardiorespiratory fitness
5	I felt lonely.	Addiction (repetitive behavior)	Varied movements	Coordination
6	I feel like I have no major complaints.	Heavy	Light movement	Agility
7	People were unfriendly.	Isolation (low self-esteem)	Large movements	Flexibility
8	I felt sad.	Loss of balance	Balance	Balance (proprioception)
9	I felt that people dislike me.	Obedient (low self-esteem)	Bold and together	Coordination
10	I could not get "going."	No response	Fast reactions	Agility & fast reactions

Figure 2. Extraction of the fitness factors from the DSM-5 criteria and CESD-10-D to develop 6 specific physical activity game tasks. CES-D-10: 10-item Center for the Epidemiological Studies of Depression Short Form; DSM-5: Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition.

	DSM-5 diagnostic criteria
1	Feelings of worthlessness or excessive or inappropriate guilt
2	Insomnia or excessive sleep
3	Depressive mood
4	Fatigue or loss of vitality
5	Psychomotor agitation or retardation
6	Depressive feelings

Fitness factors
[**Coordination**] Movement reaction time
[**Cardiovascular endurance**] Movement speed
[**Balance**] Performance time, center of mass movement range
[**Reaction time**] Performance time, movement speed, correct pairs matched
[**Muscular endurance**] Muscle balance, performance time
[**Agility & reaction time**] Reaction time, hand range of motion, and speed

Mood	Level	Contents
Happy	6	**[Let's Do It Together!]** Follow the pictures and perform the correct postures
	5	**[Cho Cho Let's Go on a Train Trip!]** Select the transport of your choice and follow the rails.
	4	**[A Breathtaking Adventure]** Travel through various paths while exploring the forest, jungle, and sky.
Unhappy	3	**[Follow Me!]** Follow the instructions of the avatar to erase the color or follow the movement.
	2	**[Rock Climbing Challenge!]** Use your arms and legs to move to points that appear in the various directions.
	1	**[Match the Flying Objects!]** Use your hands and legs to match the stimuli of the designated shape and color.

Extraction of Physical Activity Patterns From the CES-10-D

Items 1 and 2 are associated with unhappiness and depressive moods, which are reported to produce the symptom of slow movements, that is, psychomotor retardation (longer reaction times) with slow brain potentials [34]. For example, various studies have shown that gait patterns associated with sadness and depression are characterized by slower walking speed, reduced arms sign, and reduced vertical head movements [35,36]. In addition, people with depression and sadness showed larger lateral swaying and had a more slumped posture [35]. A recent review about gait, balance tasks, and posture in major mental illnesses such as depression and anxiety also indicated that evaluation and treatment programs should include specific physical movement characteristics, such as balance, gait pattern, and posture [37].

Feeling depressed is also associated with poor posture, that is, sitting in a slouched position [29]. A novel study [29] investigated whether changing posture could reduce negative affect and fatigue in people with mild-to-moderate depression undergoing a stressful task. The study found that adopting an upright posture appeared to increase positive affect, reduce fatigue, and decrease self-focus in people with mild-to-moderate

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depression. Besides, participants in the upright group spoke significantly more words than the usual posture group, used fewer first-person singular personal pronouns, but more sadness words. Comparable effects of posture were also shown to affect the ability of college students to significantly recall negative memories easily when they were sitting in a slouched posture than when they were sitting in an erect posture [38]. The authors recommended that therapists should teach their clients posture awareness and that they should sit up in an erect position during their daily lives to increase positive affect and decrease depressive symptoms [38]. Michalak et al [39] reported that even relatively minor changes in the motoric system (posture) can affect the cognitive biases in depression and suggested training patients in mindful body awareness to foster the understanding of the interplay between bodily and emotional processes.

Items 3 and 4 are questions related to fatigue, with depression strongly linked to a lack of physical activity, especially in late-life depression [40]. Mänty et al [41] showed that there are significant reductions in the isometric muscle strength (ie, knee extension, body extension, and handgrip) of older people, which highly correlate with gait speed. Similarly, Szlejf et al [42] reported that depression is associated with sarcopenia due to the low muscle strength in middle-aged and older adults. In addition, a study by Song et al [43] indicated that exercise programs such as Tai-Chi can have positive effects on middle-aged and older females by increasing their physical function in terms of muscle strength, flexibility, and endurance, as well as their depression scores. The importance of physical exercise in treating depression and the strong correlation between increased muscle strength and reduced feelings of depression have already been highlighted [44].

Item 5 is related to feelings of loneliness, with physical activity reported to contribute to a decrease in the feeling of loneliness [45]. Moreover, in a population-based observational cohort study that used comparable annual data collected between 2015 and 2019 to evaluate the effect of COVID-19 on depression and its contributing factors, the decrease in physical activity was identified as a risk factor for the worsening mental health. The authors also recommended policies to target potentially modifiable risk factors such as participating in physical activity [46]. As loneliness may be a reason why people do not want to participate in physical activity, it is important to have an easily accessible method for people to become more physically active in their daily lives [47].

Agitation is an easily observable phenomenon associated with depression [48] and can be characterized using the observation scale developed by Hurley et al [49], which includes total body movements, up and down movements, repetitive motion in place, outward motions, high pitched or loud words, repetitive vocalization, and negative words. Repetitive behaviors are shown to be related to anxiety and depression in youth with autism spectrum disorder [50].

Item 6 is a heavy feeling and so we recommend light agile movements to improve this mood. Michalak et al [35] reported on the negative effect of sadness and depression on movement/gait, describing the gait of walkers with depression as heavy, because they have larger lateral sway and walk in a slumped posture with more pronounced slower, lower arm swing and more slumped posture. We propose that light and agile movements should be introduced to counteract the feeling of heaviness. The feeling of heaviness is reported widely throughout the literature to be associated with depression, suggesting that biological and neurological mechanisms can affect physical activity, which can be explained by neurophenomenological studies and enactive dimensions of embodiment [51]. These movement-based embodied contemplative practices have been used to help alleviate depressive symptoms, with interventions using mindfulness mediation, yoga, Tai-Chi, dance, and movement therapy [51]. Recently, in a meta-analysis investigating the effectiveness of dance movement therapy as an intervention/therapy for depression, moderate effect sizes were found, and in all the cases the depression scores decreased, with the decrease continuing for several months even after the completion of the therapy [51]. Furthermore, in a multicenter, randomized control trial in Finland, dance movement therapy—performed 2 times per week for a total of 10 weeks—with standard care was shown to be an effective treatment for depression, with medium effect sizes reported at the 3-month follow-up time [52].

Item 7 focuses on reducing feelings of isolation by encouraging large movements to help improve the feeling of social belonging. Decreases in daily physical activity and increased sedentary time are related to an increased risk of ill health; furthermore, poor well-being is associated with isolation among older men and women [53]. In this study we propose that providing an opportunity to engage in physical activity and encouraging large movements could help relieve the feelings of isolation. In addition, the context and social benefits of engaging in regular leisure-time activities and physical activity are deemed to explain the reduction of depression symptoms [54]. A recent study of 3052 US adults revealed that people who could not meet the recommended daily physical activity levels as a result of the pandemic reported worse depression, loneliness, stress, and less positive mental health overall [55].

For item 8, as poor balance is associated with depressive symptoms, we focused on developing user's balance and proprioceptive neuromuscular system. Qi and colleagues [56] showed that muscular paralysis and balance problems were significantly associated with increased severities of depression (odds ratio 13.5 and 2.9, respectively), and recommended that testing for changes in balance and muscular paralysis could be useful biomarkers for assessing depression severity that could be administered regularly for monitoring patients with major depressive disorders [56]. Similarly, the "gait and brain study" showed that depressive symptoms may amplify balance problems in older adults with mild cognitive impairment during sensorimotor challenges [57]. In addition, the study showed increases in postural sway during open and closed eye conditions for patients with more depressive symptoms [57]. Likewise, Casteran et al [58] associated balance with depression by recording more sway among both male and female elderly participants with depression. As significant depressive symptoms may affect balance in the older population, it may thus also increase the potential for the risk of falls, which can be fatal

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and have a substantial impact on people with and without depression, making it more difficult to be physically active and independent.

As item 9 focuses on the person's self-esteem behavior, we hypothesized that trying to coordinate movements with an avatar may help the participant feel closer to people. The relationship between exercise, self-esteem, and depression is highlighted in numerous publications [59,60]. In children with obesity, exercise alone as a treatment was shown to be effective in reducing the feeling of low self-esteem and improving depressive symptoms [60]. In addition, the role of self-esteem in depression is reported to be a predicting factor; in other words, patients with higher gains in self-esteem over the treatment period of cognitive behavioral group therapy had strong linear declines in depressive symptoms [60]. Exercise was also shown to be effective in the older population to increase self-esteem, reduce depressive symptoms, and improve overall quality of life [61]. Many studies [51,52] included dance therapy with slow cyclical movements as an intervention, and concluded that the soothing effect of dance therapy can have positive effects on mood. Despite the vast number of studies highlighting the positive effects of physical activities/exercise on self-esteem and depressive symptoms, the exact mechanism is not well discussed [62,63]. Future studies should therefore focus on the effects that specific types of physical activity have on the various physiological mechanisms that increase self-esteem, and therefore, reduce depressive symptoms.

Item 10 focuses on the amotivation of people to exercise. For this scenario, we suggest an intervention that encourages, almost forces, a participant to move as a natural reaction to a certain stimulus. Therefore, the contents of this intervention should trigger a rapid reaction movement that should be gamified to help the participant enter flow and forget their amotivation to do any physical activity. Studies have suggested that just inducing someone to initiate a movement could help them perform more physical activity [64]. As a result of the physical activity performed, the reward system (Behavioral Activation System theory) is activated and the participant feels more at ease and experiences an improved mood [65], as it significantly reduces anger, confusion, fatigue, tension, and vigor. In addition, participation in an exercise program reduces negative mood. Research shows that slow rhythmical movements at the frequency of the respiratory sinus arrhythmia (approximately 0.1 Hz) will help the participant feel "being in the groove" and is associated with more efficient blood circulation and increases in heart rate. Furthermore, these movements are shown to have a positive effect on the automatic nervous system [66]. Although there is not much research on the effect of explosive fast reaction time movements, we hypothesize that because it is the opposite to what the participant is used to, it should help initiate movement and eventually improve mood.

Assessment of Depressive Severity to Customize User's Level of Difficulty

The user's game level was customized according to the 9-item Patient Health Questionnaire (PHQ-9) score, as shown in Table 1 and Figure 2. The user with the most severe depression symptoms, with a PHQ-9 score between 22 and 27, had to perform sets 1-1, 1-2, 1-3 then 2-3, up to 6-3, for a total of 8 sets. If users had a PHQ-9 score between 10 and 15, they had to perform sets 3-1, 3-2, 3-3 up to 6-3, for a total of 6 sets. If users had a PHQ-9 score between 1 and 3, they only had to perform sets 6-1 (warm-up), 6-2 (slowly increased intensity), and 6-3 (main exercise intensity), for a total of 3 sets. Based on the gamification principles, each set lasted approximately 5 minutes, which was shown to be the optimal time for someone to maintain concentration during a game [67].

Table 1. Allocation of the games required according to the severity of diagnostic score.

Mood and level	PHQ-9[a] score	CES-10-D[b] score
Happy		
6	1-3	0
5	4-6	1-2
4	7-9	3-4
Unhappy		
3	10-15	5-6
2	16-21	7-8
1	22-27	9-10

[a]PHQ-9: 9-item Patient Health Questionnaire.

[b]CES-D-10: 10-item Center for the Epidemiological Studies of Depression Short Form.

Customized Exergames Matrix

Based on the principles of physical activity training methods, the interactive game has basic, intermediate, and advanced stages (Figure 3). The basic stage allowed the participants to warm-up and stretch. The intermediate stage increased the movement range and speed of the required moves for the participant to progress gradually. The advanced stage was performed only after the basic and intermediate stages had been completed fully, and it required a full range of upper and lower body movements with high intensity and relative speed.

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Figure 3. Sequence of games according to the PHQ-9 score. PHQ-9: 9-item Patient Health Questionnaire.

Baseline diagnostic result		PHQ-9 score	Basic stage	Intermediate stage	Advanced stage
Happy	Level 6	1-3	Set 6-1	Set 6-2	Set 6-3
	Level 5	4-6	Set 5-1	Set 5-2	Set 5-3
	Level 4	7-9	Set 4-1	Set 4-2	Set 4-3
Unhappy	Level 3	10-15	Set 3-1	Set 3-2	Set 3-3
	Level 2	16-21	Set 2-1	Set 2-2	Set 2-3
	Level 1	22-27	Set 1-1	Set 1-2	Set 1-3

Gamification for Player's Flow

Gamification has been used to motivate users to practice games daily. The primary motivation for designing these games was to have fun and invoke a flow experience. They were designed to stimulate the users to continue, and it was crucial that the levels were neither too hard nor too easy; therefore, we assigned difficulty to each level according to the user's ability and previous performance. Each of the presented games has pass and fail criteria to provide users with a sense of achievement to help motivate them, which will enable them to perform to their fullest potential so that they progress. In addition, after each attempt at a stage, the user is provided with game-dependent feedback: score, reaction times, movement speeds, and the number of correct postures. The game visuals and audio stimulation were designed to be aesthetically pleasing and easy to understand to help maintain immersion and make the game more user-friendly.

Results

Game 1: Collect the Space Treasure

In this game, the user must collect all the space treasure that is flying toward them using their hands and legs. Based on the advice of an expert group comprising game designers, mental health practitioners, and user interface/design experts, various shapes and colors were selected with the main aim to help increase interest in the game. As the level increases, the number and types of shapes and the speed at which they approach increase. Furthermore, the user's range of movement is progressively increased from the objects being closer to the body to within the reach of the body without moving the trunk and finally to moving both arms and trunk to reach the objects. Each level takes up to 5 minutes to complete, with meteorites, stars, and flying saucers appearing sequentially in the basic level. At the intermediate level, there is a mixed appearance of meteorites, stars, and flying saucers, and at the advanced level, there is a mixed appearance of meteorites, stars, and flying saucers and colors.

At the start of the game, the user selects the space that suits their avatar's attire and then their level (Figure 4). There are 149 target objects at the basic level, from which 70 must be matched correctly for successful completion. There are 220 target objects at the intermediate level, from which 110 must be matched correctly for successful completion. There are 315 target objects at the advanced level, from which 150 must be matched correctly for successful completion.

Next, the user reads the game instructions on how to play and is guided though the process of getting ready and starting (Figure 5). Currently, the instructions are in the Korean language, as the test bed is located in Korea.

The game then begins with an alien saying, "Let's go to match some flying objects." After matching the objects, as illustrated in Figure 6, the result is displayed as a mission success or failure. Here, one can see a mixture of combinations with the increasing range of movement and complexity by using both hands and following a sequence of movements (Figure 6). The user's reaction time should improve as they have to match the objects in specific sequences and train their cardiovascular system owing to constant movement.

Figure 4. Game's opening scene (left), user selecting their avatar (center), and user selecting their level (right).

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Figure 5. Guidance to get ready (center) and begin (right) with sound effects and music in the background to help maintain immersion.

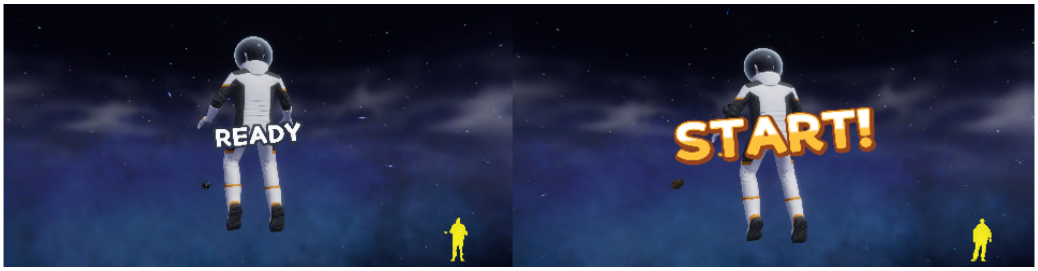

Figure 6. Reaching to the right (left), double-handed movement expanding to the full range of movement (center), and mission success screen (right).

Game 2: Rock Climbing Challenge

In this game, the user must maintain rock-climbing–type poses to advance up the wall (Figures 7 and 8). Muscle endurance is required in this game as the user must maintain certain poses, such as balancing on 1 leg and reaching. Initially, the poses use only the left and right hands; however, as the levels increase, the arms and legs must move together in more challenging poses. The complexity of the poses and the required range of movement increase as the game progresses. This game should help users improve their strength by requiring them to hold poses for a few moments. In addition, their joint range of motion will be increased when performing elongated stretching movements.

The user is required to select their avatar and the level of difficulty (Figure 7). After reading the instructions on how to play, the game begins (Figure 8). Figure 8 illustrates the sequence of movement required by the player to proceed to the next required pose. The user must move the hands and feet in the correct direction and pose for the level to proceed, and there will be movement noise to indicate that the sequence is correct and a visual stating “Good.”

There are 3 levels, each of which takes approximately 5 minutes to complete. There are 50 poses at the basic level, and each must be held for 4 seconds; 25 poses must match correctly for successful completion. There are 60 poses at the intermediate level, and each must be held for 3 seconds; 30 poses must match correctly for successful completion. There are 75 poses at the advanced level, and each must be held for 2 seconds; 40 poses must match correctly for successful completion.

Figure 7. Game’s opening scene (left), user selecting their avatar (center), and user selecting their level (right).

Figure 8. Starting screen to prepare user for the game (left), with guidance indicated with a circle (center). After a few minutes of exercise there is a time to recover and the user is encouraged to stretch and take a breath (right).

Game 3: Follow Me

In this game, the user must follow the avatar’s movement by erasing the coverings on top of the painting to reveal the original painting underneath (Figures 9-11). As with the previous games, the user begins by selecting the avatar (male or female) from the 3 levels (basic, intermediate, and advanced). The game begins after the instructions are displayed. The painting is divided into different blocks, allowing the user to erase the coverings to reveal the original painting underneath. As the

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level progresses, more squares (3×3 to 5×5) covering the painting appear, which requires more movement from the user to erase the painting coverings. The primary difference between the basic, intermediate, and advanced levels is that the user at the basic level only erases the coverings of the underlying art in their preferred order. However, for intermediate and advanced levels, the user must erase the coverings in separate movements, which are a combination of erasing a few coverings. In addition, the movements required to erase the covering takes more movement, and the user needs to move progressively further away from their standing position and reach up and down to various heights. Through repeated use of this game, the user's range of motion should increase due to reaching up, down, left, and right in multiple directions (Table 2).

Figure 9. Game's opening scene welcoming you to the art museum (left), selection of avatar (center), and selection of levels, from basic to advanced (right).

Figure 10. Game's how to play screen (left), ready to play screen (center), and basic level (right).

Figure 11. Indication that first painting is finished (left); user is instructed to rest and stretch for a few minutes (right).

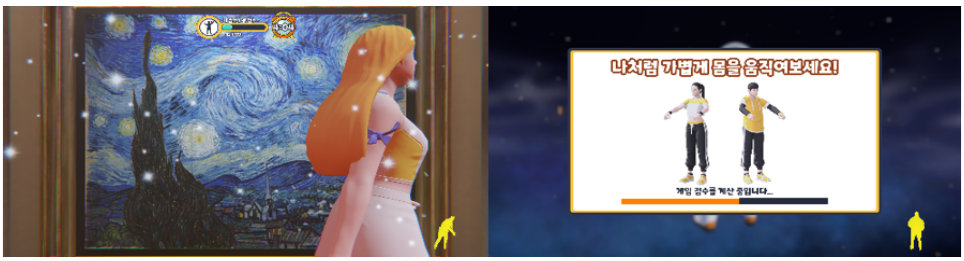

Table 2. Progression of levels and difficulty in game 3.

Levels	Number of physical activity movements	Pass criteria
Basic	• 4 seconds for 2 coverings (1×2) changes to 3 seconds for 4 spaces (2×2) to be erased • 4 seconds for 9 coverings (3×3) performed 2 times • 2 seconds for 16 coverings (4×4) performed 2 times changes to 2 seconds for 20 coverings (4×5) performed 2 times • 16 seconds (randomly divided) performed 4 times	60/121 need to be correct
Intermediate	• 12 seconds per movement (a combination of coverings; 4-4-4); a total of 12 movements • 6 seconds per movement (2-2-2); a total of 6 movements • 12 seconds per movement (4-4-4); a total of 5 movements • 6 seconds per movement (2-2-2); a total of 10 movements	15/33 need to be correct
Advanced	• 12 seconds per movement (4-4-4); a total of 4 movements • 6 seconds for each movement (2-2-2); a total 32 movements • 4 seconds per movement (simultaneous); a total of 15 movements	25/51 need to be correct

Game 4: A Breathtaking Adventure

In this game, the user must navigate through the allocated paths, moving within a beautiful natural background (Figure 12). As with the previous games, the user begins by selecting the avatar (male or female) from the 3 levels (basic, intermediate, and advanced). The game begins after the instructions are displayed (Figure 13). The user progresses through the levels by first walking along an easy path, which then slowly becomes more challenging as they are required to pass narrow bridges, swaying

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rope bridges, and even crossing stepping stones (Figure 14). The user's balance is improved by playing this game, as they must control their steps and directions to navigate. In addition, the user must avoid various obstacles and must move left or right to do so. The user must have 80/160, 40/80, and 40/85 successful steps at the basic, intermediate, and advanced levels, respectively. There is background noise such as natural sounds, special visual effects, and audio and visual guidance to make the game more intuitive and user-friendly and help immerse in and enjoy it.

Figure 12. Game's opening scene welcoming the user (left), selection of avatar (center), and selection of levels, from basic to advanced (right).

Figure 13. Game's how to play screen (left). The basic level showing walking on a path (right).

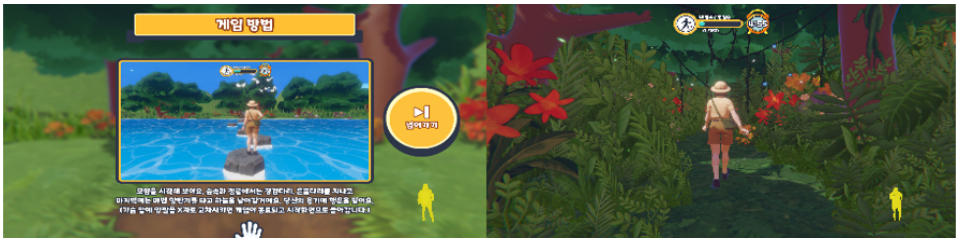

Figure 14. Game progresses to walking over narrow bridges (left), advanced-level walking across stepping stones (center), advanced-level walking on different paths, including narrow, wide, and more complex (right).

Game 5: Cho Cho Let's Go on a Trip!

In this game, the user must walk or jog on the spot to control the speed and movement of a train (Figures 15-17). The game strengthens the cardiovascular system because the user must keep walking or jogging slowly on the spot. Users can select from various modes of transport such as bicycles, cars, or trains. The levels progress by increasing the users' movement speed as they move through the numerous natural backgrounds, such as by the sea, through the countryside, or city. The basic level starts with slow walking, normal speed walking, and then a slow jog, requiring the user to maintain continuous movements for more than 120 seconds out of 250 seconds to proceed to the next level. At the intermediate level, it progresses with slow walking, normal speed walking, a slow jog, and then a normal speed jog, with the user required to maintain movement for 180 continuous seconds out of 240 seconds. For the advanced level, the user performs interval-style training with a slow walk (30 seconds), light run (30 seconds), fast walk (30 seconds), run (30 seconds), slow walk (30 seconds), fast walk (30 seconds), light jog (30 seconds), and finishing with a run (60 seconds). The movement speeds were controlled by the tempo of the audio: 70 bpm for a slow walk (Adagio), 118 bpm for a fast walk (Allegretto), 156 bpm for a light run (Vivace), and 168 bpm for a run (Presto). There was 5-10-second rest between each of the required poses. The criteria for passing the most advanced stage 3 required the user to maintain movement for at least 200 seconds out of the 270 seconds.

Figure 15. Game's opening scene welcoming you to go on a trip (left), selection of mode of transport (center), and selection of levels, from basic to advanced or exit (right).

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Figure 16. Game's how to play screen (left) and basic-level cycling on a path (right).

Figure 17. Game progresses to traveling through towns and cities (left), traveling by the sea (center), and traveling through the countryside (right).

Game 6: Let's Do It Together

In this game, the user must maintain postures so that their avatar can pass through the advancing walls with particular body shapes (Figures 18 and 19). The game starts with the user selecting their avatar (male or female) and then selecting levels 1, 2, or 3 (Figure 18). Instructions on how to play appear once the user understands and selects the next button to start the game. At the basic and intermediate levels, the user must maintain the particular poses to pass through the advancing walls, as shown in Figure 19. At the advanced level, the user must move according to the instructions on the screen. The movement at this level is not in particular poses; however, they must move on the ground left, right, forward, back, and in a combination of numbers, arrows, shapes, and animals (Figures 20 and 21). In the game, 11 motions appear randomly and are repeated. A movement is recognized as a success when it maintains a synchronization rate of 80%, according to the level. For the basic stage, the success criteria were 15 correct movements out of 30. For the intermediate stage, the success criteria were 22 correct movements out of 43, and for the advanced stage, the success criteria were to match 57 out of 114 pictures in total.

Figure 18. Game's opening scene welcoming you to dance together (left), selection of avatar (center), and selection of levels, from basic to advanced or exit (right).

Figure 19. Game's how to play screen (left), ready to play by matching the shape coming toward the player (center), and another and more difficult shape to match (right).

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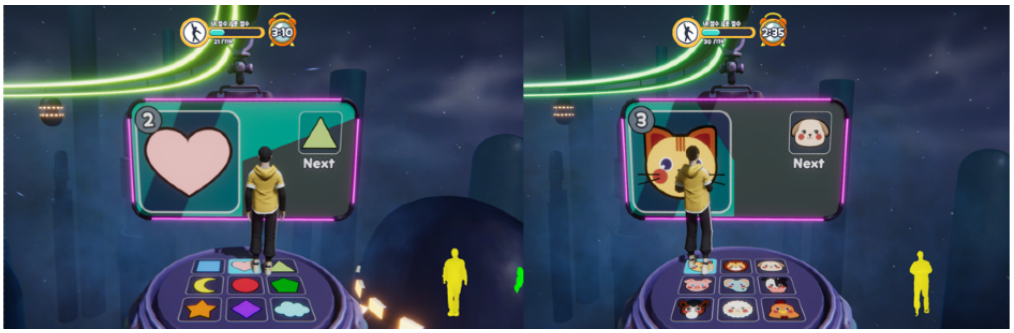
Figure 20. Visual feedback for movement on the ground numbers and arrows (left to right).

Figure 21. Visual feedback for movement on the ground shapes and animals (left to right).



Discussion

Principal Findings

This article provides a detailed framework for applying the gamification principles to develop the contents of an exergame for depression based on clinically proven depression diagnostic criteria. The diagnostic criteria we selected to provide a structure for developing a systematic approach for treating depression were based on the DSM-5 depression diagnostic criteria and CES-D-10. Based on these criteria, we propose diverse physical activity–based interventions focusing on various related fitness factors, such as cardiovascular factors and strength.

We are currently seeking Institute Review Board approval to help determine the feasibility of the content and users' experience. In this planned pilot test, we will obtain feedback on the usage of each of the games and their associated contents and visual and audio feedback, which will provide qualitative feedback for the service user to help improve the content through a refinement of the intervention. Upon completion of a series of tests and retests with relevant stakeholders, a randomized controlled trial will be conducted to check the effectiveness of the treatment or intervention and its cost-effectiveness relative to the standard methods of treatment and intervention.

A major strength of digital solutions is the exponential expandability of technology to reach users; however, this comes with the need for users to have digital literacy to use the content and initial investment in the hardware. A major limitation is the users' need for hardware that is compatible with the developed content. Currently, having access to depth cameras is challenging; however, we are confident that, as they are instrumental and there is a growing amount of evidence demonstrating their vast applications in the field, they will continue to be developed and made more accessible in the future.

This study is beneficial as it provides a structured framework for developing digital content based on physical activity interventions for solving various mental health issues. By leveraging digital solutions, we hope that the overall cost of treatment for mental health issues will be reduced and that the suggested solution will be expandable for an exploding population that requires the management of mental health, particularly in the post-COVID-19 pandemic era.

Conclusions

This study highlights the application of gamification principles to develop interactive physical activity content for a depression intervention game. In addition, we provide a structured methodology for developing content associated with depression movement characteristics (kinematics). Further research is required to determine the effectiveness and user experience of an exergame to prevent, manage, and treat depression in a range of low- to high-severity participants.

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Conflicts of Interest

None declared.

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Abbreviations

CES-D-10: 10-item Center for the Epidemiological Studies of Depression Short Form
DSM-5: Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition
PHQ-9: 9-item Patient Health Questionnaire

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Original Paper

Virtual Reality Technology in Cognitive Rehabilitation Application: Bibliometric Analysis

Danni He[1], BSc; Shihua Cao[2], PhD; Yuchao Le[1], BSc; Mengxin Wang[1], BSc; Yanfei Chen[1], BSc; Beiying Qian[1], BSc

[1]School of Nursing, Hangzhou Normal University, Hangzhou, China

[2]Nursing Department, Hangzhou Normal University Qianjiang College, Hangzhou, China

Corresponding Author:
Shihua Cao, PhD
Nursing Department
Hangzhou Normal University Qianjiang College
No.16 Xuelin St, Jianggan District
Hangzhou City, Zhejiang Province
Hangzhou, 310036
China
Phone: 86 13777861361
Email: csh@hznu.edu.cn

Abstract

Background: In recent years, with the development of computer science and medical science, virtual reality (VR) technology has become a promising tool for improving cognitive function. Research on VR-based cognitive training has garnered increasing attention.

Objective: This study aimed to investigate the application status, research hot spots, and emerging trends of VR in cognitive rehabilitation over the past 20 years.

Methods: Articles on VR-based cognitive rehabilitation from 2001 to 2021 were retrieved from the Web of Science Core Collection. CiteSpace software was used for the visual analysis of authors and countries or regions, and Scimago Graphica software was used for the geographic visualization of published countries or regions. Keywords were clustered using the gCLUTO software.

Results: A total of 1259 papers were included. In recent years, research on the application of VR in cognitive rehabilitation has been widely conducted, and the annual publication of relevant literature has shown a positive trend. The main research areas include neuroscience and neurology, psychology, computer science, and rehabilitation. The United States ranked first with 328 papers, and Italy ranked second with 140 papers. Giuseppe Riva, an Italian academic, was the most prolific author with 29 publications. The most frequently cited reference was “Using Reality to Characterize Episodic Memory Profiles in Amnestic Mild Cognitive Impairment and Alzheimer’s Disease: Influence of Active and Passive Encoding.” The most common keywords used by researchers include “virtual reality,” “cognition,” “rehabilitation,” “performance,” and “older adult.” The largest source of research funding is from the public sector in the United States.

Conclusions: The bibliometric analysis provided an overview of the application of VR in cognitive rehabilitation. VR-based cognitive rehabilitation can be integrated into multiple disciplines. We conclude that, in the context of the COVID-19 pandemic, the development of VR-based telerehabilitation is crucial, and there are still many problems that need to be addressed, such as the lack of consensus on treatment methods and the existence of safety hazards.

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KEYWORDS

virtual reality; cognitive rehabilitation; bibliometric analysis; CiteSpace; gCLUTO; rehabilitation; cognitive disorder; visual content analysis

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Introduction

Background

Cognition refers to the mental processes associated with acquiring knowledge and converting it into mental activities [1]. Cognitive function is composed of multiple cognitive domains such as memory, language comprehension ability, spatial orientation, executive ability, and computing power [2]. Cognitive dysfunction refers to a decline in one or more domains of cognition caused by various factors. The main symptoms include poor responsiveness, apathy, reduced proactive behavior, and short-term memory impairment, which in turn affects the individual's activities of daily living [3].

Cognitive impairment increases stroke risk in older adults [4]. In the presence of a stroke, dementia onset might occur 10 years earlier, with up to one-third of persons who have experienced a stroke being diagnosed with dementia [5,6]. Therefore, it is crucial to explore treatments that could prevent or delay cognitive impairment. Owing to the limited effectiveness of pharmacological treatments, nonpharmacological interventions to treat cognitive deficits have been widely studied in recent years [7]. Several advantages of computer-assisted cognitive rehabilitation have been demonstrated, such as individualized, flexible, and economical programs that provide immediate feedback [8]. In this type of treatment, technologies such as robots, noninvasive brain stimulation, wearable systems, and neuroprosthetics were used. Among these, virtual reality (VR) shows great potential for neurorehabilitation [9].

A VR system can be defined as a highly interactive 3D digital media environment. Users can receive multisensory feedback, such as auditory, tactile, and visual feedback, in the simulated environment [10]. Developed in the 1990s and used as a tool to assess and treat diseases [11], VR has the advantage of providing an environment that simulates the sensation of the real world, combined with the situations and physical needs in daily lives [9]. Several studies have confirmed the effectiveness of VR in treating diseases such as anxiety, cognitive decline in older adults, and bulimia nervosa [12]. Jang et al [13] found that sensory feedback during VR training affected neuroplasticity and promoted brain reorganization. Optale et al [14] conducted a randomized controlled trial to examine the effectiveness of a VR intervention in older adults with memory deficits. The control group was treated with music therapy and the treatment group underwent 3 months of VR memory intervention. After completing the training series, the VR group showed significant improvements in memory tests, especially in long-term recall, with an effect size of 0.7 [14]. The study by Burdea et al [15] showed that individuals with chronic poststroke symptoms in the VR group achieved significant improvements in depression (effect size=0.75) and cognition (effect size=0.46; $P<.05$). These examples suggest that VR can be used to improve impaired cognitive functions.

Research Problem and Aim

Bibliometrics is the cross-disciplinary science of quantitative analysis of all knowledge carriers using mathematical and statistical methods. It is a commonly used method to identify the development of a certain field [16]. The advantage of bibliometrics is that it can help scholars quickly grasp the research hot spots and development trends of a specific research area by analyzing citations, cocitations, distribution of countries or regions, authors, and journals in the research field [17]. The study by Keshner et al [18] applied topic modeling methods to 3141 publications included in the Web of Science (WoS), highlighting the research emphasis on VR in rehabilitation. Studies on VR-based cognitive rehabilitation have been published worldwide. However, there is little research that analyzes the scientific output in this field from a bibliometric and visualization perspective. Understanding the research status and hot spots in this field is of great significance for promoting the rehabilitation of disorders related to cognitive impairment. Therefore, based on the WoS Core Collection, this study comprehensively analyzed the research field to provide a reference for future research.

Methods

Data Sources and Search Strategy

In this study, only articles and reviews published in English between 2001 and 2021 were included. The data used in this study were downloaded from the WoS Core Collection. The search strategy was as follows: (1) topic ("reality" OR "VR") AND ("cognition" OR "cognitive function" OR "cognitive impairment" OR "cognitive dysfunction" OR "cognitive rehabilitation"); (2) the document type was selected as "Article" OR "Review"; (3) the language was selected as "English"; (4) the dates of the search were from January 1, 2001, to December 20, 2021. In total, 1286 documents met the selection criteria.

Screening Strategy

The structured approach by Kable et al [19] to searching and critiquing the research literature was used to guide and support this review. In this study, 2 reviewers (DH and YC) screened the search results independently, and the results were then cross-checked. Upon encountering any disagreements, a third researcher (SC) was consulted. All the researchers received training in document retrieval and screening by studying the textbook *Medical Literature Information Retrieval* [20].

WoS generates and provides keywords plus for research publications. Keywords plus are words and phrases that are generated using algorithms based on the titles referenced or cited in the documents. WoS-assigned keywords plus express the knowledge structure of the discipline and interconnectedness of different research areas [21]. During the literature selection process, the titles, abstracts, keywords, and keywords plus of the articles were used to accept or remove published material. Articles that did not contain content related to cognition and VR in these parts were considered to be irrelevant to the topic. The author, title, publication year, and journal were used to identify duplicate records. In total, 20 duplicate records and 7 irrelevant papers were identified and removed. A total of 1259 articles were exported in the form of a full record and cited references, saved as plain text files, and stored in download_txt format (Figure 1).

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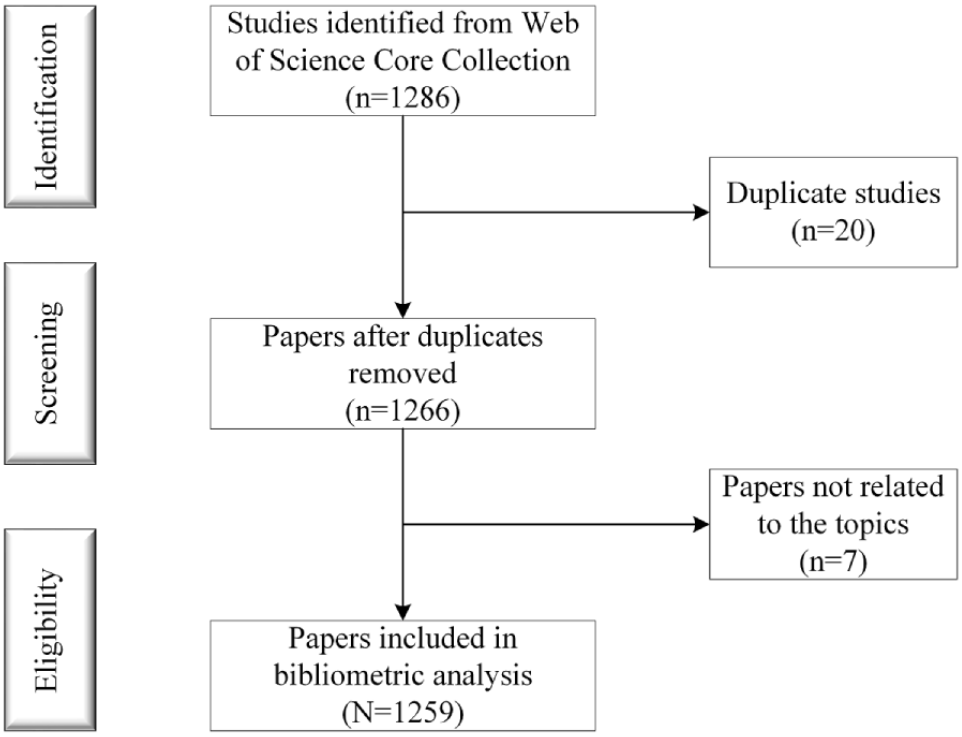
Figure 1. Flowchart of literature selection.



Data Analysis

In this study, CiteSpace (version 5.8.R2; Drexel University), Scimago Graphica (version 1.0.16; Scimago lab), and gCLUTO (version 1.0; Kerapis lab) software were used to perform the bibliometric visual analysis. CiteSpace was used to analyze the distribution of countries or regions, authors, journals, and cocited references. Scimago Graphica was used to generate geographic visualization maps of the countries or regions. gCLUTO was used for the keyword clustering analysis. Repeated bisection was chosen as the clustering method. The similarity was calculated by choosing the cosine function. The clustering criterion function was set to I^2. The clustering results with a high ISim and low ESim were selected [22], and the number of clusters was adjusted.

Ethical Considerations

No application for an ethical permit was submitted for this paper. According to the Chinese Hospital Association, an ethics review was not required for this secondary analysis of published data.

Results

The Annual Trends of Publications

The number of documents published in each period reflects the development trend of research in the field. Figure 2 plots the distribution of annual research publications on the application of VR in cognitive rehabilitation in the past 20 years.

Microsoft Excel 2019 was used to conduct linear regressions using the Trendline function and polynomials. The dotted lines in Figure 2 are polynomial fitting created by the application, which predict future publication trends in this field. The trendline equation is $y = 1.22x^2 - 10.17x + 25.54$. In this equation, y represents the number of publications, and x represents the ID of publication years in temporal order. Model fitting curve revealed a positive trend in annual publication numbers over the past 20 years (R^2=0.977; the closer R^2 is to 1, the better the fit of the trendline). The trend line shows that the number of publications will continue to increase in the future.

According to the number of publications, the publication year can be divided into 3 periods: from 2004 to 2011, from 2012 to 2016, and from 2017 to 2021. As shown in Figure 2, no relevant papers were published before 2004. From 2004 to 2016, the number of articles in this field increased annually; however, the growth rate was relatively slow. The number of publications in 2017 reached 101, surpassing 100 for the first time. From 2017 to 2021, the number of published articles increased significantly, indicating that an increasing number of scholars have begun to focus on the potential of VR in the field of cognitive rehabilitation.

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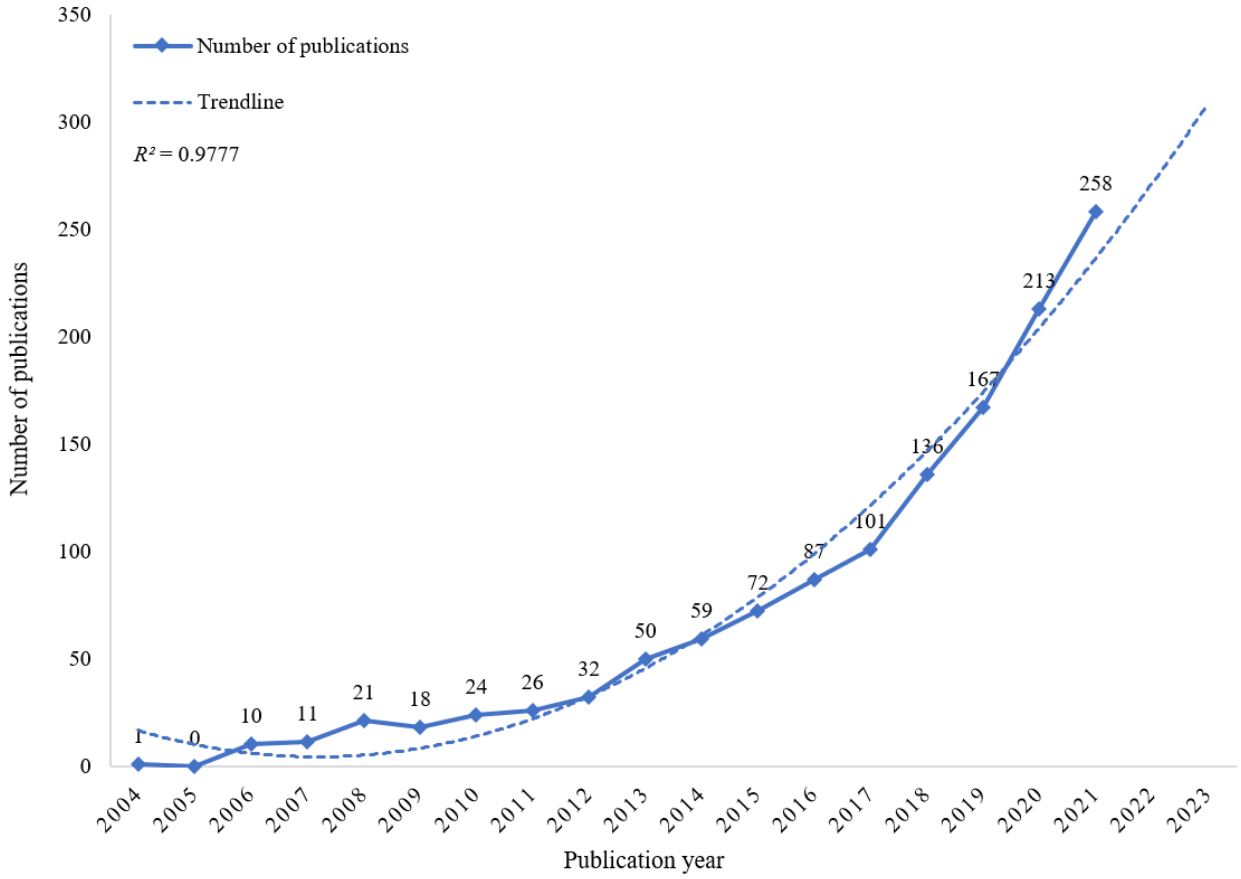
Figure 2. Annual publication outputs and the model fitting curve of time trend of virtual reality in cognitive rehabilitation.



Popular Research Themes

Each publication indexed in the WoS is associated with one or more subject categories (SCs). We identified the top 10 SCs (Table 1). The most popular research areas were neurosciences and neurology (n=392), followed by psychology (n=314), computer science (n=131), and rehabilitation (n=125). SC "computer science" accounted for only 5.2% (7/134) of publications during period 1 but increased to 10.3% (93/907) during period 3. SC "health care sciences and services" accounted for 0.8% (1/134) of publications during period 1 and then increased to about 4.9% (44/907) during period 3.

The 10 most frequently studied diseases are listed in Table 2. Aging is listed in the table because human aging is usually accompanied by typical structural and neurophysiological changes in the brain and varying degrees of cognitive decline [23]. Reviews that aimed to investigate the status of VR aid treatment for neurological or psychiatric disorders were not included in the statistics because they did not investigate a specific disease. Stroke, dementia, and mild cognitive impairment (MCI) were the 3 major research areas of the publications.

Table 1. The number of publications in the top 10 Web of Science (WoS) subject categories for the total study period and for each period.

WoS subject categories	Total (N=1416), n (%)	Period 1 (n=134), n (%)	Period 2 (n=375), n (%)	Period 3 (n=907), n (%)
Neurosciences and neurology	392 (27.7)	35 (26.1)	109 (29.1)	248 (27.3)
Psychology	314 (22.2)	32 (23.9)	84 (22.4)	198 (21.8)
Computer science	131 (9.2)	7 (5.2)	31 (8.3)	93 (10.3)
Rehabilitation	125 (8.9)	16 (11.9)	36 (9.6)	73 (8.1)
Psychiatry	124 (8.8)	17 (12.7)	34 (9.1)	73 (8.1)
Engineering	110 (7.8)	7 (5.2)	24 (6.4)	79 (8.7)
Geriatrics and gerontology	71 (5.0)	6 (4.5)	21 (5.6)	44 (4.9)
Health care sciences and services	54 (3.9)	1 (0.8)	9 (2.4)	44 (4.9)
Education and educational research	48 (3.4)	7 (5.3)	11 (2.9)	30 (3.3)
Behavioral science	47 (3.4)	6 (4.5)	16 (4.2)	25 (2.8)

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Table 2. Top 10 most frequently studied diseases in virtual reality–based cognitive rehabilitation (N=1259).

Ranking	Disease	Publication, n (%)
1	Stroke	104 (8.26)
2	Dementia	91 (7.23)
3	Mild cognitive impairment	83 (6.59)
4	Aging	75 (5.96)
5	Brain injury	64 (5.08)
6	Schizophrenia spectrum and other psychotic disorders	60 (4.77)
7	Parkinson disease	45 (3.57)
8	Multiple sclerosis	22 (1.75)
9	Autism spectrum disorder	20 (1.59)
10	Posttraumatic stress disorder	11 (0.87)

Distribution of Countries or Regions

The data were imported into CiteSpace, "Country" was selected as a node, the number of objects in each time slice was set to 50, and the minimum spanning tree algorithm was used to draw the countries or regions cooperation network map (Figure 3). A total of 1259 articles were published in 62 countries or regions. The size of the node label represents the number of papers published in the country or region. The larger the node font, the higher the number of papers published. The purple outer circle of the node indicates that the node has a high centrality. The centrality of a node is a graph-theoretical property that measures the importance of the node's position in a network. A commonly used centrality metric is betweenness centrality. CiteSpace helped identify pivotal points by measuring the betweenness centrality of a node. It quantifies the probability that the node is on an arbitrary shortest path in the graph. Nodes with high betweenness centrality tend to be found in paths connecting different specialties or tipping points in a network [24]. The betweenness centrality of a node *v* is defined as follows as g(v):

$$g(v) = \sum_{s \neq v \neq t} \sigma_{st}(v) / \sigma_{st} \quad \textbf{(1)}$$

where σ_{st} is the total number of shortest paths from node *s* to node *t* and $\sigma_{st}(v)$ is the number of shortest paths from *s* to *t* going through *v* [25].

Figure 3. Distribution of publications from different countries.

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As shown in Table 3, in the field of VR on cognitive rehabilitation, the most significant number of publications came from the United States (328/1259, 26.05%), followed by Italy (140/1259, 11.12%), the United Kingdom (130/1259, 10.33%), China (115/1259, 9.13%), and Germany (101/1259, 8.02%). These 5 countries published 64.65% (814/1259) of the total number of articles. Among the top 10 countries, the United States, the United Kingdom, Australia, Spain, France, Germany, and Canada showed a high degree of centrality.

Scimago Graphica software was used to analyze the countries with more than 5 publications to generate a geographic visualization map (Figure 4). The lines in the figure represent cooperation between countries, and the edge width of the lines represents the intensity of cooperation. It can be seen that the United States, the United Kingdom, Australia, China, and other countries have actively cooperated with other countries. Moreover, many European scholars have shown interest in the application of VR in cognitive rehabilitation and have conducted international cooperation to a certain extent.

Table 3. Countries with the top 10 publications on virtual reality in cognitive rehabilitation (N=1259).

Ranking	Country	Publication, n (%)	Centrality
1	United States	328 （26.05）	0.36
2	Italy	140 （11.12）	0.06
3	United Kingdom	130 （10.33）	0.35
4	China	115 （9.13）	0.09
5	Germany	101 （8.02）	0.1
6	Australia	90 （7.15）	0.2
7	Spain	81 （6.43）	0.18
8	Canada	81 （6.43）	0.1
9	France	80 （6.35）	0.15
10	The Netherlands	75 （5.96）	0.05

Figure 4. Geographic locations of countries with more than 5 publications.

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Authors and Cooperative Relationships

A total of 537 authors have published articles on the application of VR in cognitive rehabilitation (Figure 5). Giuseppe Riva was the most prolific author, with 2.3 (29/1259) of articles, followed by Rocco Salvatore Calabro with 1.91 (24/1259) of articles. Rocco Salvatore Calabro (24/1259, 1.91%), Rosaria De Luca (20/1259, 1.59%), Maria Grazia Maggio (14/1259, 1.11%), and Antonino Naro (14/1259, 1.11%) conducted active cooperation and communication, forming the largest author collaboration network. It is worth noting that the centrality of the top 10 authors was 0 (Table 4), suggesting that the influence of the authors on the of VR in cognitive rehabilitation needs to be improved.

Figure 5. Visualization map of authors involved in the application of virtual reality in cognitive rehabilitation.

Table 4. Top 10 productive authors on the application of virtual reality in cognitive rehabilitation (N=1259).

Ranking	Author	Publication, n (%)	Centrality
1	Giuseppe Riva [9,12,26,27]	29 （2.3）	0
2	Rocco Salvatore Calabro	24 （1.91）	0
3	Rosaria De Luca	20 （1.59）	0
4	Maria Grazia Maggio [28]	14 （1.11）	0
5	Antonino Naro [28]	14 （1.11）	0
6	Silvia Serino [26,27]	13 （1.03）	0
7	Placido Bramanti	12 （0.95）	0
8	Anat Mirelman	9 （0.71）	0
9	Alfredo Manuli [28]	8 （0.64）	0
10	Pietro Cipresso	8 （0.64）	0

Cocited Academic Journals

The journal cocitation analysis revealed the overall structure of the subject and the characteristics of a journal. As shown in Table 5, the most cited journal is *Plos One* (466/28,765, 1.62%). Among the top 10 academic journals, the highest impact factor is neurology (impact factor 9.910). Furthermore, it can be seen that half of the journals in the table belong to quartile ranking position 1. The dual-map overlay of journals represents the topic distribution of the academic journals. In the dual map, the map of the citing journals is on the left, the map of the cited journals is on the right, and the colored paths between them suggest the cited relationships. There are 5 main citation paths, with 2 blue paths, 2 pink paths, and 1 orange path (Figure 6), representing that the documents published in psychology, education, or social journals are often cited by psychology, education, health, neurology, sports, ophthalmology, molecular biology, or immunology journals, and the documents published in molecular biology or genetics journals are often cited by psychology, education, health, neurology, sports, or ophthalmology journals.

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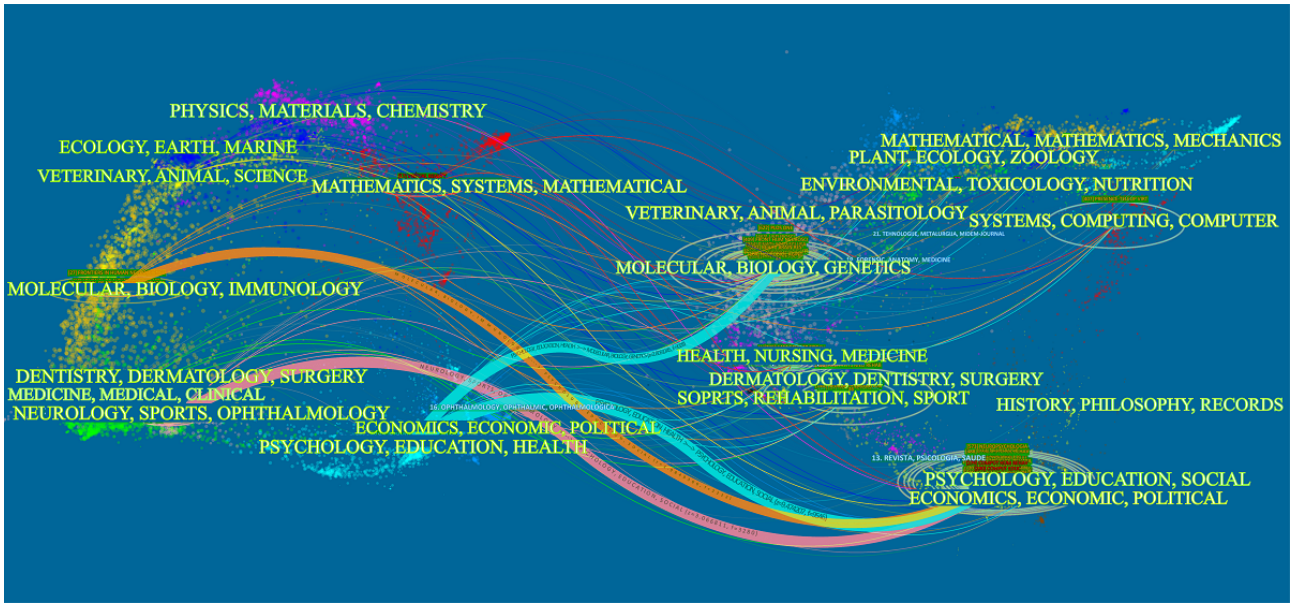
Table 5. Top 10 cocited journals that published articles on the application of virtual reality in cognitive rehabilitation (N=28,765).

Ranking	Cocited journal	Citation, n (%)	Impact factor based on Clarivate Analytics Journal Citation Report (2020)	JCR[a]
1	Plos One	466 (1.62)	3.240	Q[b]2
2	Neuropsychologia	377 (1.31)	3.139	Q1
3	Frontiers in Human Neuroscience	353 (1.23)	3.169	Q3
4	Cyberpsychology Behavior and Social Networking	349 (1.21)	4.157	Q1
5	Frontiers in Psychology	319 (1.11)	2.988	Q2
6	Neurology	318 (1.11)	9.910	Q1
7	Archives of Physical Medicine and Rehabilitation	305 (1.06)	3.966	Q1
8	Neuroscience	295 (1.03)	3.590	Q2
9	Neuroimage	268 (0.93)	6.556	Q1
10	Presence: Teleoperators and Virtual Environments	265 (0.92)	0.597	Q4

[a]JCR: Clarivate Analytics Journal Citation Report.

[b]Q: quartile ranking position.

Figure 6. The dual-map overlay of journals on the application of virtual reality in cognitive rehabilitation.



Cocited References

As a statistical approach to detecting research trends, cocitation refers to the phenomenon in which 2 or more articles are cited by other articles at the same time. When a group of authors cite a common set of documents, these cocitations indicate documents that may contain concept symbols [29]. Cited articles are the foundations upon which current research is being conducted; they represent the intellectual base [30,31]. These publications may contain foundational theories, groundbreaking early works, and methodological principles in the field [31]. Among the 821 cocited references retrieved, Table 6 shows the 10 most frequently cited references, of which "Using Virtual Reality to Characterize Episodic Memory Profiles in Amnestic Mild Cognitive Impairment and Alzheimer's Disease: Influence of Active and Passive Encoding" is the most frequently cited (n=26).

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Table 6. Top 10 cocited references on the application of virtual reality in cognitive rehabilitation.

Ranking	Reference	Number of citation	Centrality
1	Using Virtual Reality to Characterize Episodic Memory Profiles in Amnestic Mild Cognitive Impairment and Alzheimer's Disease: Influence of Active and Passive Encoding	26	0
2	Cognitive Training on SStroke Patients via Virtual Reality-Based Serious Games	25	0.02
3	A Feasibility Study With Image-Based Rendered Virtual Reality in Patients With Mild Cognitive Impairment and Dementia	23	0.04
4	Computerized and Virtual Reality Cognitive Training for Individuals at High Risk of Cognitive Decline: Systematic Review of the Literature	23	0.06
5	The Effectiveness of Virtual Reality for People With Mild Cognitive Impairment or Dementia: a Meta-analysis	22	0.01
6	Benefits of Virtual Reality-Based Cognitive Rehabilitation Through Simulated Activities of Daily Living: a Randomized Controlled Trial With Stroke Patients	22	0.07
7	A Succinct Overview of Virtual Reality Technology Use in Alzheimer's Disease	22	0.14
8	Effects of Virtual Reality-Based Physical and Cognitive Training on Executive Function and Dual-Task Gait Performance in Older Adults With Mild Cognitive Impairment: a Randomized Control Trial	21	0
9	Effects of Virtual Reality-Based Training With BTs-Nirvana on Functional Recovery in Stroke Patients: Preliminary Considerations	20	0.01
10	Virtual Reality in the Assessment, Understanding, and Treatment of Mental Health Disorders	20	0.03

Distribution of Keywords

By analyzing the keywords, we can summarize the study topics in a specific field and explore hot spots. Data cleaning was performed to remove coding errors, because different articles may use different keywords to refer to the same concept. For example, "older people," "elderly," and "old adult" represent the same concept, they were recorded as "old adult," and "cognitive impairment" and "cognitive dysfunction" were combined into the keyword "cognitive impairment." In all 1259 publications, we obtained 544 keywords. The keyword "virtual reality" has the highest frequency of 851. Other keywords with high frequency include "cognition" (n=236), "rehabilitation" (n=193), "performance" (n=164), "older adult" (n=151), "memory" (n=143), "dementia" (n=143), "Alzheimer's disease" (n=141), "mild cognitive impairment" (n=125), and "environment" (n=123; Table 7).

CiteSpace burst-detection algorithms were adapted for detecting sharp increases in interest in a specialty [24]. According to keyword burst detection, Table 8 lists the top 20 keywords with the strongest citation bursts. The red line represents the duration of the burstness. Among these words, "social cognition" (6.22) was the strongest burst keyword during the period between 2004 and 2021, followed by "environment" (6.00), "brain injury" (5.86), "spatial memory" (5.55), and "episode memory" (5.51).

Table 7. Top 10 keywords related to the application of virtual reality in cognitive rehabilitation.

Ranking	Keyword	Frequency	Centrality
1	Virtual reality	851	0.06
2	Cognition	236	0.1
3	Rehabilitation	193	0.04
4	Performance	164	0.17
5	Older adult	151	0.05
6	Memory	143	0.07
7	Dementia	143	0.04
8	Alzheimer's disease	141	0.06
9	Mild cognitive impairment	125	0.04
10	Environment	123	0.09

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Table 8. Top 20 keywords with the strongest citation burst related to the application of virtual reality in cognitive rehabilitation.

Ranking	Keywords	Strength	Start year	End year	2004-2021
1	Brain injury	5.86	2006	2013	
2	Environment	6.00	2006	2009	
3	fMRI[a]	4.14	2007	2015	
4	Strategy	3.45	2007	2015	
5	Performance	3.41	2007	2012	
6	Spatial memory	5.55	2008	2014	
7	Skill	3.45	2009	2014	
8	Cognitive function	4.78	2009	2013	
9	Hippocampus	5.35	2010	2017	
10	Ecological validity	3.52	2013	2017	
11	Neuropsychological assessment	3.88	2013	2016	
12	Human	3.85	2013	2015	
13	Spectrum disorder	3.65	2013	2014	
14	Social cognition	6.22	2014	2017	
15	Prefrontal cortex	3.99	2014	2017	
16	Episodic memory	5.51	2015	2017	
17	Serious game	3.59	2017	2018	
18	Randomized controlled trial	3.40	2018	2019	
19	Telerehabilitation	3.36	2019	2021	

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Ranking	Keywords	Strength	Start year	End year	2004-2021
20	Recognition	3.34	2019	2021	

[a]fMRI: functional magnetic resonance imaging.

Different clusters can be formed based on the keywords with different degrees of closeness. Identifying these clusters can provide an intuitive understanding of various hot subfields of research in a particular field. The keyword co-occurrence matrix was imported into gCLUTO for clustering analysis. A keyword clustering hill plot was generated (Figure 7). Each hill represents a cluster, and there are 7 clusters. The shape of the hill is a Gaussian curve. The height of the hill is proportional to the similarity of the documents within the cluster, while the volume of the hill is proportional to the number of documents contained within the cluster. Only the color of the top of the hill is meaningful, with a red bias representing a low intraclass SD and a blue bias representing a high intraclass SD [22]. The dendrogram from clustering shows that the hot spots of research on the application of VR in cognitive rehabilitation are focused on MCI in older adults, Alzheimer disease (AD), stroke, and traumatic brain injury (Figure 8). Cluster 6 was the largest cluster and contained 11 keywords. The high-frequency keywords were “neuropsychological assessment,” “presence,” “embodiment,” and “virtual reality.”

A time-zone view can help show changes in the research trends in a field over time. From the time-zone view, nodes in the same period can be gathered in the same time zone. The year represents the time when the keyword first appears. The link between keywords means that they appear in the same document. It can be seen from Figure 9 that there is no relevant document was published before 2004. Keywords appeared more intensively from 2006 to 2016, but most were related to diseases, such as “brain injury,” “depression,” “Alzheimer’s disease,” and “attention deficit hyperactivity disorder (ADHD).” Keywords related to psychology and psychiatry, such as “anxiety,” “schizophrenia,” and “depression,” appeared in the early stages of VR-based cognitive rehabilitation development. As time goes on, research hot spots such as “telerehabilitation” and “post-traumatic stress disorder” emerged.

Figure 7. Keyword clustering hill plot of publications related to the application of virtual reality (VR) in cognitive rehabilitation.

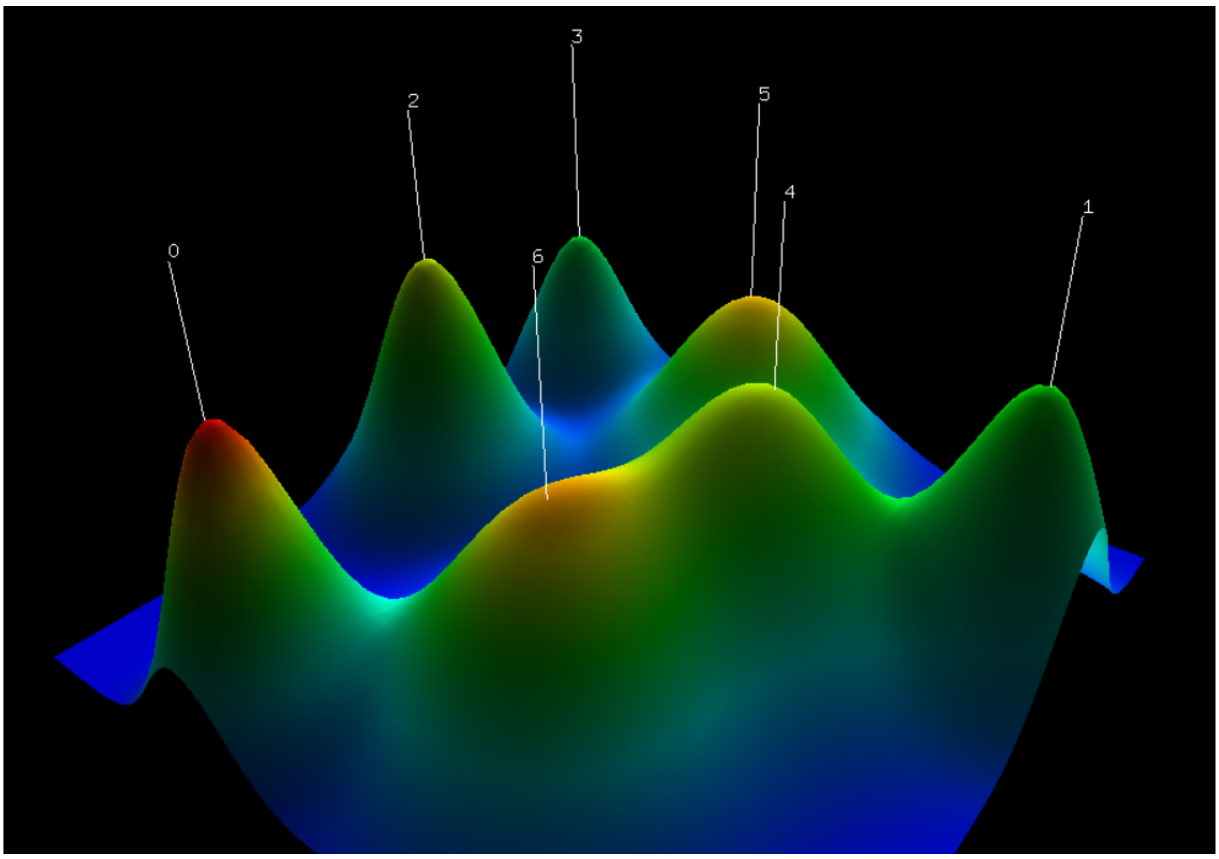

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Figure 8. Clustering dendrogram of keywords of publications related to the application of virtual reality in cognitive rehabilitation. EEG: electroencephalogram.

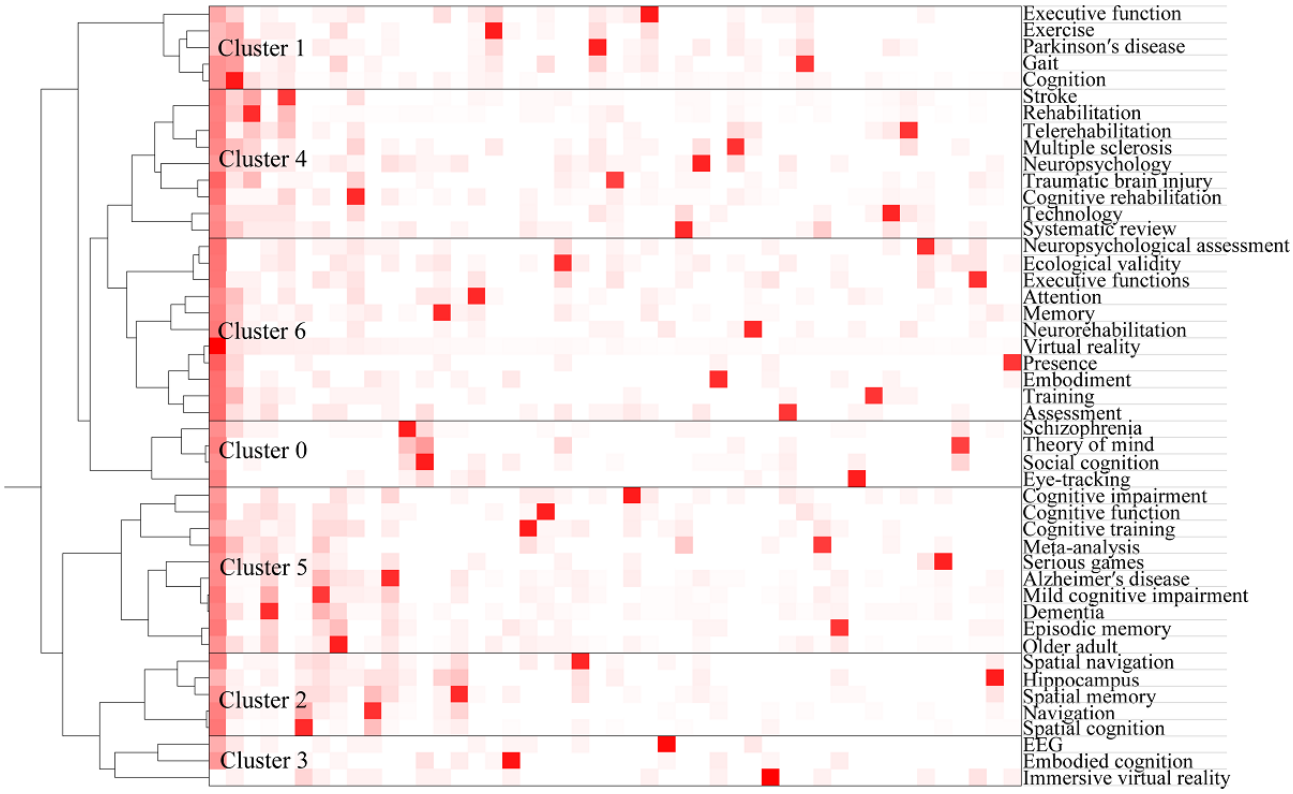
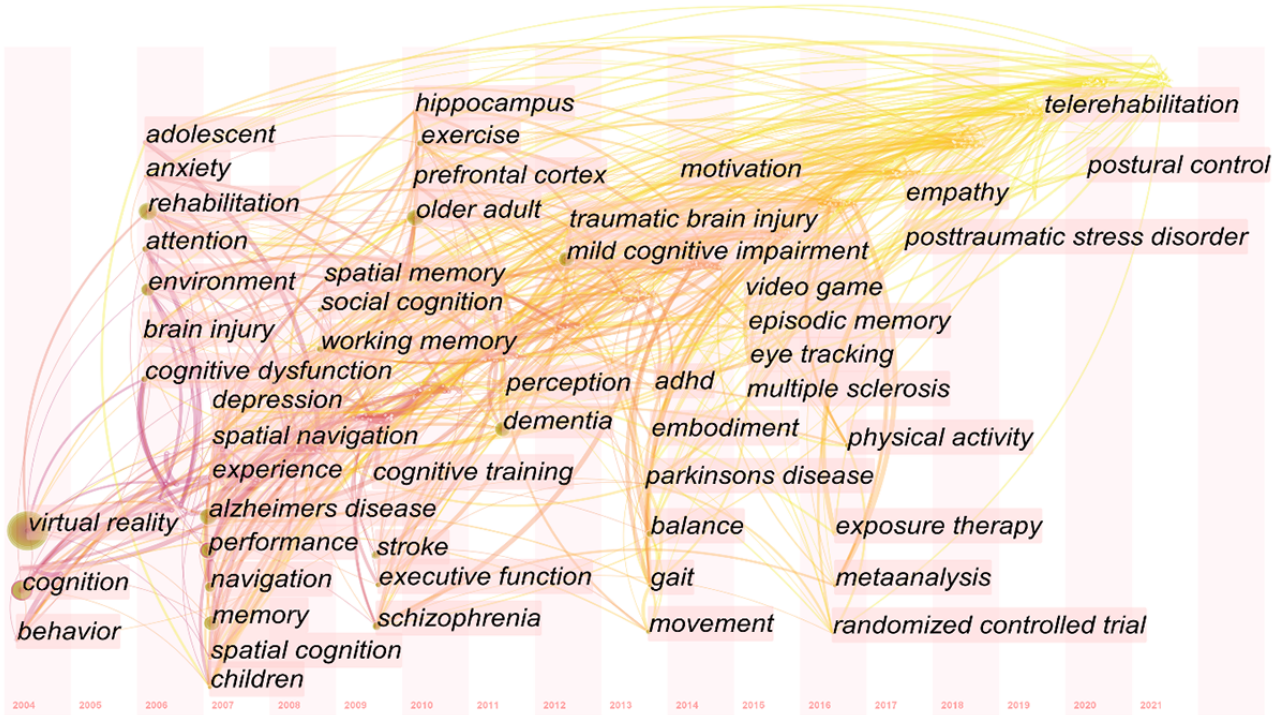


Figure 9. The keywords time-zone view of publications related to the application of virtual reality in cognitive rehabilitation.



Institutions

A total of 65.7% (830/1259) of documents on VR-based cognitive rehabilitation were funded. The top 10 funding institutions by the number of publications are listed in Table 9. Half of the top 10 funding support institutions are from the United States, indicating that the United States has strong support and substantial funding for research in this field.

Table 10 presents the research areas funded by these institutions. We noted that they tend to fund multiple disease areas rather than a single disease. The National Institute on Aging (NIA) seems to place greater emphasis on research in neurosciences

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and neurology and geriatrics and gerontology. Similarly, research in psychiatry is more likely to be funded by National Institute of Mental Health (NIMH).

Table 9. Funding institutions for publications related to the application of virtual reality in cognitive rehabilitation (N=830).

Rank	Funding	Country	Publication, n (%)
1	United States Department of Health Human Services	United States	82 (9.9)
2	National Institutes of Health United States	United States	82 (9.9)
3	European Commission	European Union	75 (9)
4	National Science Foundation	United States	43 (5.2)
5	National Natural Science Foundation of China	China	30 (3.6)
6	German Research Foundation	German	25 (3)
7	National Institute of Mental Health	United States	23 (2.8)
8	United Kingdom research innovation	United Kingdom	19 (2.3)
9	Canadian Institutes of Health Research	Canada	19 (2.3)
10	National Institute on Aging	United States	18 (2.2)

Table 10. Top 10 funding institutions and research area on virtual reality in cognitive rehabilitation.

	HHS[a] (n=92), n	NIH USA[b] (n=91), n	European Commission (n=94), n	NSF[c] (n=43), n	NSFC[d] (n=29), n	DFG[e] (n=27), n	NIMH[f] (n=27), n	UKRI[g] (n=23), n	CIHR[h] (n=24), n	NIA[i] (n=22), n	Total (n=472), n
Neurosciences and neurology	31	32	31	4	9	5	8	9	8	9	146
Psychology	21	21	18	13	3	10	5	7	7	2	107
Computer science	1	1	7	11	7	4	1	0	0	0	32
Rehabilitation	9	10	6	2	1	1	0	0	2	4	35
Psychiatry	12	12	10	0	1	1	10	3	1	1	51
Engineering	3	0	11	9	5	3	0	1	1	0	33
Geriatrics and gerontology	4	4	2	1	1	0	0	1	2	4	19
Health care sciences and services	4	4	0	0	0	2	1	0	1	1	13
Education and educational research	2	2	1	2	0	0	1	1	0	0	9
Behavioral sciences	5	5	8	1	2	1	1	1	2	1	27

[a]HHS: United States Department of Health and Human Services.
[b]NIH USA: National Institutes of Health.
[c]NSF: National Science Foundation.
[d]NSFC: National Natural Science Foundation of China.
[e]DFG: German Research Foundation.
[f]NIMH: National Institute of Mental Health.
[g]UKRI: UK Research Innovation.
[h]CIHR: Canadian Institutes of Health Research.
[i]NIA: National Institute on Aging.

Discussion

General Information

According to the annual publication output, the publication years could be divided into 3 phases. The period from 2004 to 2011 could be considered the first phase. The number of publications increased slowly during this stage. The period 2012 to 2017 could be seen as the second phase. In 2012, Google unveiled "Project Glass," with the promise to deliver an augmented reality head-mounted display device to the masses. Oculus released the first working prototypes of the Oculus Rift VR headset. Both the quality and availability of VR hardware

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and software components have changed significantly during this time. Thus, period 2 and period 3 demonstrate an increased interest in computer science. In the last phase (2017-2021), there was a sharp growth in publications. Trends in home computing and entertainment made user-friendly, robust, and polished extended VR systems available for personal ownership in the 2010s, accelerating the pace of growth in VR telehealth research [32]. Since then, remote health care apps have developed significantly, such as VR tele–mental health, telemonitoring of fully remote interventions, and specialized medical equipment with VR and augmented reality [33]. These results suggest that research is becoming more mature, and researchers have developed considerable interest in the application of VR in cognitive rehabilitation.

VR-based cognitive rehabilitation contributions come from all over the world, including the United States, Italy, the United Kingdom, China, Germany, Australia, Spain, Canada, France, and the Netherlands taking positions of prominence. China is the only Asian country among them, which indicates that scholars from Asian countries have not attached much importance to research in this field. In contrast, funders and scholars in the United States have shown continued research interest. A bibliometric analysis of VR and health care have similarly demonstrated that the United States was the country with the highest contribution (26.4% vs 26.1% in this report) [34]. Among the top 10 contributing countries, the United States is the most prominent in terms of funding for scientific research. According to the last census of the population, nearly 1 in 5 people have a disability in the United States. By 2050, the number of individuals with disabilities is estimated to exceed 64 million. With more people who experience disabling health events (eg, stroke or traumatic brain injury) surviving and living longer, the number may be even higher [35].

Over the past 20 years, several reimbursement methods for medical rehabilitation have been developed in the United States. One important transition was the inclusion of “rehabilitative and habilitative services and devices” as one of the 10 “essential benefits” of the Affordable Care Act in 2010 [35]. In April 2013, a number of public and private institutions and agencies joined together to launch Brain Research Through Advancing Innovative Neurotechnologies (BRAIN), with the NIH (part of the United States Department of Health & Human Services) playing an important role. The BRAIN aims to help researchers to seek new ways to treat, cure, and even prevent brain disorders. By 2021, the NIH has awarded more than 1100 awards to hundreds of researchers, totaling approximately US $2.4 billion [36]. Owing to the cross-cutting nature of this project, the NIH BRAIN Initiative is managed by 10 NIH institutes and centers, including the NIA and NIMH listed in this paper.

In the field of pharmaceutical science, 67% to 97% of drug development is conducted by the private sector [37]. However, we note that most funded studies identified in this paper are supported by public institutions (NIH, National Science Foundation, Canadian Institutes of Health Research, German Research Foundation, National Natural Science Foundation of China, UK Research Innovation, and European Commission; the NIA and NIMH are both institutes and centers that make up the NIH, which is a part of the United States Department of Health and Human Services). This finding may be because some private companies prefer to provide the supply of VR products or devices rather than financial support. A second explanation may be that private industries that develop and manufacture VR products do not have the means to fund research in the VR-based cognitive rehabilitation field fully on a sufficiently large scale. A third way to understand these results is that market risk and uncertainty are too high to elicit private investment. According to Sharma et al [38], VR technology is still in its early stages, and obtaining funds from investors is one of the most significant problems because predicting the level of public acceptance is difficult. It is clear that more research is needed to analyze the reasons for this variation between types of funders and their impact.

Among prolific authors, Giuseppe Riva, an Italian academic, has the highest number of publications. Over the past decade, his research on VR-based cognitive rehabilitation has focused on various neurodegenerative disorders such as AD, Parkinson disease (PD), and MCI. A previous bibliometric analysis of VR research in MCI by Zhu et al [39] similarly demonstrated that Giuseppe Riva is the most popular scholar. The other 3 authors in the top 10 list of this study were also in the top 10 list of Zhu et al [39]; they are Silvia Serino, Anat Mirelman, and Pietro Cipresso. It is worth noting that the top 10 authors have a centrality of 0, which indicates that their influence in this research field needs to be further improved. Rocco Salvatore Calabro, Rosaria De Luca, Maria Grazia Maggio, Antonino Naro, Placido Bramanti, and Alfredo Manuli have published articles in the VR-based cognitive rehabilitation field as a research team. Therefore, the research topics of these authors are highly similar. Similarly, Giuseppe Riva, Silvia Serino, and Pietro Cipresso are from Milan, Italy; they formed a cohesive team. Moreover, Anat Mirelman , a professor at Sackler School of Medicine and Sagol School of Neuroscience at Tel Aviv University, ranked eighth. Her research interests in VR-based cognitive rehabilitation are in understanding aging and neurodegenerative diseases such as PD. The research topics of the authors in the top 10 list of this study are relatively concentrated, which implies that cooperation between different research teams was not close. Cross-cooperation between researchers with different disciplinary backgrounds can promote the progress of a certain research subject [40]. We suggest that awareness of this discrepancy may encourage researchers to share knowledge and experience from different disciplines.

The cocitation frequency reflects the quality and influence of the journal. Among the 10 journals with high cocitation frequency, half of the journals belong to quartile ranking position 1. These journals have an important impact on the international community, indicating that the application of VR in cognitive rehabilitation has received worldwide attention.

Through the analysis of cocited documents, it can be found that the paper with the highest citation frequency in the past 20 years is “Using Virtual Reality to Characterize Episodic Memory Profiles in Amnestic Mild Cognitive Impairment and Alzheimer’s Disease: Influence of Active and Passive Encoding.” We have mentioned that compared with the traditional language test, the VR test can test memory in a way that is closer to the memory needs of daily life [41].

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Research Hot Spots and Frontiers

Both stroke and dementia can pose a significant threat to older adults; they often frequently coexist and share certain risk and protective factors [4]. The VR tasks to assess and train episodic memory of older adults are a research hot spot in geriatrics. VR provides an immersive experience and provides more natural interactions with the surrounding environment. There is a trend in research that more immersive VR systems promote improved episodic memory performance [42]. Within this context, interest in examining presence in experiments that investigate the effects of immersion on memory in virtual environments has started to grow.

MCI is common in older populations, and its prevalence increases with age [43]. It is a significant risk factor for AD. AD is irreversible and presents with significant treatment difficulties. Early identification and intervention are critical for improving the prognosis of MCI [44,45]. Numerous randomized controlled trials have been conducted on drug therapies for MCI. However, when compared with drug therapy, VR-based interventions seem to be more cost-effective and accessible [45].

Cognitive impairment no dementia has been commonly considered to be a normal consequence of brain aging [46]. However, some subtypes of cognitive impairment no dementia often represent early dementia and affect dementia and incident disability [4]. Perhaps due to the fact that older adults with cognitive impairment no dementia may be a potential target population for VR-based cognitive training to prevent or delay the onset of dementia, this field is a research hot spot. Meanwhile, age-associated memory impairment has been of interest to scholars because of the difficulties it may engender in the performance of everyday activities.

Introducing an embodied cognition approach helps to integrate the recovery of motor functions into cognitive rehabilitation [47]. Embodied cognition states that there is a close relationship between the body and mind (or cognition). Motor programming and execution depend on the interaction between the body, cognition, and the external environment. Therefore, peculiar motor tasks contextualized in a specific environment can enhance cognitive functions [28]. Bocanegra et al [48] interpreted PD within an embodied cognitive framework. According to them, language and cognition are grounded in lower-level sensorimotor mechanisms. As Tuena et al [26] claimed, VR can influence cognitive processes as an embodied tool.

Posttraumatic brain injury (TBI) is one of the main research hot spots in the field of VR-based cognitive rehabilitation. According to a study conducted by Maas et al [49], epidemiological patterns of TBI in high-income countries are changing. TBI because of traffic-related incidents has decreased, and older age of patients with TBI because of falls is increasing. Moreover, aging is closely linked to AD, PD, MCI, and cognitive impairment with no dementia. In general, the research participants of cognitive rehabilitation based on VR are mainly older adults, regardless of whether their cognitive decline is caused by disease.

The use of immersive VR was beneficial in managing a spectrum of mental disorders, such as the treatment of persecutory delusions in the context of schizophrenia spectrum disorders [50], social adaptation skills training for children with autism spectrum disorder [51], and exposure therapy for combat-related posttraumatic stress disorder in the active-duty military [52].

VR-based rehabilitation is not a well-defined multidisciplinary field, but a network of traditional disciplines that utilize common technology [18]. Therefore, there are significant differences between VR-based rehabilitation methods. For example, VR-based exposure therapy has been used for eating disorders [53] and combat-related posttraumatic stress disorders [52]. For older people, VR-based therapies integrated with movement therapy have been found to improve spatial navigation [54]. Furthermore, some studies have applied game elements to VR-based rehabilitation such as serious games and virtual spatial wayfinding games [55,56].

Since the existing studies are diverse, more implementation studies are needed in different populations to evaluate the effectiveness and maximize the potential of VR in cognitive rehabilitation. In addition, as Birckhead et al [57] claimed, it is essential to develop and evaluate VR therapy within a common scientific framework.

Application and Development Trend of Research

Over the past 20 years, VR has been widely used in cognitive rehabilitation for MCI, AD, PD, stroke, brain injury, and posttraumatic stress disorder. With the development of high-performance mobile computing and various software programs, highly immersive VR has become available and affordable [58]. Currently, commonly used VR systems include Kinect from the United States, Nintendo Wii from Japan, HTC Vive from Taiwan, China, and Samsung Gear VR from South Korea. Using these VR systems in cognitive rehabilitation, we expect further improvement in patient compliance and interest in therapy.

With the continuous interpersonal transmission of COVID-19, patients' access to health care is limited, but VR technology can overcome this limitation to some extent. The VR-based telerehabilitation provides an immersive environment for the patient while allowing remote monitoring of the rehabilitation progress. Studies have shown that VR-based telerehabilitation cost less than clinic-based rehabilitation programs [59,60]. However, the safety of VR-based telerehabilitation requires further assessment because the home environment is not under the control of medical staff. VR-related side effects may cause physical risks to people who are sensitive to motion sickness or those with impaired function [61]. Therefore, future research should be devoted to assessing the safety of VR-based telerehabilitation in a large patient sample to guide clinical practice.

In this study, we found that the psychology and psychiatry field is a growing area of research in VR-based cognitive rehabilitation, which is consistent with a previous study [62]. Traditional therapeutic tools are limited to psychotherapy and drug therapy. The development of VR technology has promoted

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its application in this field, including a series of studies aimed at assessing and improving symptoms of schizophrenia [63], as well as VR emotion recognition tasks aimed at treating facial emotion recognition disorders in patients with neurological and psychiatric disorders in recent years [64,65]. To develop VR into a mature tool for improving mental health, researchers need to integrate knowledge from health care, computer science, neuroscience, psychology, social cognition, multisensory perception, and multimedia development in an interdisciplinary approach [27] and specifically combine user needs. This means that research on VR-based cognitive rehabilitation should consider more stakeholders such as patients, clinicians, therapists, nurses, and software developers. Better quality research is needed to explore the potential of VR technology in different disciplines and develop more patient-appropriate intervention strategies.

Strengths and Limitations

To our knowledge, this is the first bibliometric analysis of research on VR-based cognitive rehabilitation. By including SCs, keywords, countries or regions, authors, cited journals, cited references, and funding institutions in the analysis, we were able to demonstrate a more comprehensive current situation of VR in cognitive rehabilitation. However, this study searched only 1 database, implying that it probably ignored high-quality literature in the field. In addition, the data were last updated in December 2021. As the literature in the database is constantly updated, the retrieval results of this study may differ from the actual number. The third limitation relates to the CiteSpace visual atlas. There is no standard method for setting thresholds and pruning mode in the process of generating the visual network, and as such, these elements are somewhat subjective.

Conclusions

On the basis of the WoS database and Scimago Graphica, gCLUTO, and CiteSpace software, this study presented the research overview of the application of VR in cognitive rehabilitation scientifically and intuitively. The bibliometric analysis of articles shows that research on VR-based cognitive rehabilitation has developed intensively over the past 20 years, which is embodied in the increase in the number of papers in core journals and the enhancement of the cooperative research network between countries or regions and authors. The United States and its public foundations played a leading role in this field. This paper highlights neuroscience and neurology, psychology, computer science, and rehabilitation as the main research areas in this field. VR-based cognitive rehabilitation is mainly used to treat mental disorders, brain diseases, and nervous system diseases, but a standard treatment method has not yet been developed. Moreover, this paper raises questions that require further research regarding safety hazards in VR-based remote cognitive rehabilitation and reasons for variation between types of funders.

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Conflicts of Interest

None declared.

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Abbreviations

AD: Alzheimer disease
BRAIN: Brain Research Through Advancing Innovative Neurotechnologies
MCI: mild cognitive impairment
NIA: National Institute on Aging
NIH: National Institute of Health
NIMH: National Institute of Mental Health
PD: Parkinson disease
SC: subject category
TBI: posttraumatic brain injury
VR: virtual reality
WoS: Web of Science

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Original Paper

An Analysis of Priorities in Developing Virtual Reality Programs for Core Nursing Skills: Cross-sectional Descriptive Study Using the Borich Needs Assessment Model and Locus for Focus Model

EunYoung Jeong[1], PhD; JunSeo Lim[2], PhD

[1]Department of Nursing, Wonkwang University, Jeonbuk, Republic of Korea

[2]Research Institute of Nursing Science, College of Nursing, Seoul National University, Seoul, Republic of Korea

Corresponding Author:
JunSeo Lim, PhD
Research Institute of Nursing Science
College of Nursing
Seoul National University
103 Daehak-ro
Jongno-gu
Seoul, 03080
Republic of Korea
Phone: 82 1091100844
Email: junseo@snu.ac.kr

Abstract

Background: There are limitations to conducting face-to-face classes following the recent COVID-19 pandemic. Web-based education is no longer a temporary form of teaching and learning during unusual events, such as pandemics, but has proven to be necessary to uphold in parallel with offline education in the future. Therefore, it is necessary to scientifically organize the priorities of a learner needs analysis by systematically and rationally investigating and analyzing the needs of learners for the development of virtual reality (VR) programs for core nursing skills (CNS).

Objective: This study aimed to identify the priorities of learners' needs for the development of VR programs for CNS using the Locus for Focus Model and Borich need assessment model.

Methods: The participants included nursing students in South Korea who were in their second year or higher and had taken courses in fundamental nursing or CNS-related classes. The survey took place from May 20 to June 25, 2021. A total of 337 completed questionnaires were collected. Of these, 222 were used to conduct the final analysis. The self-report questionnaire consisted of 3 parts: perception of VR programs, demand for developing VR programs, and general characteristics. The general characteristics of the participants were analyzed using descriptive statistics. To determine the priority of the demand for developing VR programs for CNS, the Locus for Focus Model and the Borich priority formula were used.

Results: In all, 7 skills were identified as being of the top priority for development, including intramuscular injection, intradermal injection, tube feeding, enema, postoperative care, supplying oxygen via nasal cannula, and endotracheal suction.

Conclusions: The analysis showed that nursing students generally needed and prioritized the development of VR programs for the nursing skills involving invasive procedures. The results of this study are intended to help in various practical education classes using VR programs in nursing departments, which are currently facing difficulties in teaching CNS on the web owing to COVID-19.

(JMIR Serious Games 2022;10(4):e38988) doi:10.2196/38988

KEYWORDS

core nursing skills; virtual reality; Borich priority formula; Locus for Focus Model; need assessment; nursing education

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Introduction

Nursing education is aimed at ensuring the provision of high-quality nursing services by identifying and responding appropriately to various needs of nursing recipients through theoretical and practical education. Regarding practical training, the Korean Accreditation Board of Nursing Education (KABONE) selected 20 basic and frequently implemented nursing skills in nursing practice as core nursing skills (CNS). CNS are the essential nursing skills that nurses must possess. Moreover, it is recommended to instill these skills in nurses by training them using the theoretical background related and in addition to the skills [1].

Traditional core nursing practice training in nursing schools is conducted in a way that enables students to directly practice the relevant skills face to face in the practice room using models and others after receiving theoretical and demonstrative education from an educator, such as a professor or practical instructor, who is proficient in technical skills. However, there have been limitations to conducting face-to-face classes following the COVID-19 pandemic. Consequently, web-based classes using webcams have been activated. Web-based education, which is currently being implemented at many universities, is no longer a temporary form of teaching and learning during unusual events, such as pandemics, but has been proven to be necessary to uphold in parallel with offline education in the future [2]. Unlike web-based theoretical education, web-based education on CNS is limited in that students learn nursing skills and improve their actual clinical performance by watching videos and learning about the skills. Therefore, there is a pressing need to develop high-level educational tools that can be provided to students learning on the web.

To overcome the limitations of core nursing practice training conducted through web-based education, a system similar to the actual clinical field in virtual reality (VR) could be built. VR provides a more optimized and immersive learning experience as well as a self-directed and practical learner-centered learning environment for individual learners, allowing them to learn without temporal and spatial limitations in a virtual environment [3]. However, neither educators nor learners are accustomed to using cutting-edge VR technology and equipment; therefore, it is not very common in education. Developers are also not actively introducing or investing in new technologies owing to the economic burden of purchasing expensive development equipment, rapid technological development, and uncertainty in commercial feasibility [4].

In health care and medical fields, it was difficult to find studies on 3D VR–related educational content before 2005. However, active research has been conducted since 2006, with 10 studies published in 2008 and 2010. A total of sixty-two 3D VR–related studies were published in the health care and medical field from 1990 to 2013 [5], of which studies on health care and medical education accounted for the biggest proportion with 34 (55%) studies; 23 (68%) of the 34 studies were conducted on nursing-related 3D VR. 3D VR educational content used in nursing education is based on themes, such as disaster-related scenarios, postpartum bleeding simulation, and nutrition, rather than CNS, as well as focusing on the scenario-oriented simulation education field to manage "situations" that may occur in the nursing field [5]. A systematic literature review including studies on nursing education using 3D VR targeting published up to November 2018 reported that there were no studies conducted in South Korea [6]. Moreover, 4 (57%) studies, more than half of the 7 studies, were conducted in the United States. Only 2 (29%) studies used 3D VR educational content while offering induction catheterization technology education. The remaining 5 (71%) were analyzed as 3D VR simulation education using scenarios [6].

The development of educational programs begins with conducting a learning needs analysis (LNA) of learners who are end users. Diagnosing and analyzing the exact needs of learners determines participation in adult education and is an essential procedure for verifying the need for education beforehand [7]. An LNA also provides educators with the information they need to develop, plan, and implement educational strategies and achieve the educational goals of their institution [8]. Therefore, it is necessary to scientifically organize the priorities of an LNA by systematically and rationally investigating and analyzing the needs of learners for the development of VR programs for CNS. An LNA is aimed at investigating the difference between "what should be" and "what is," analyzing the priority according to the difference, determining the priority, and finding an optimal solution [9]. Therefore, this study aimed to identify the top priority in the development of VR programs for CNS using LNA prioritization methods—such as the 2-tailed *t* test, Borich priority formula, and the Locus for Focus Model (LFM)—together and to suggest implications for the development of VR programs for CNS, hence improving educational outcomes through systematic prioritization.

Methods

Study Aim and Design

This cross-sectional descriptive study aimed to identify development priorities by analyzing the development needs for CNS-related VR programs for nursing students.

Participants

The participants of this study included nursing students in South Korea who were in their second year or higher and had taken courses in fundamental nursing or CNS. The survey took place from May 20 to June 25, 2021. A total of 337 copies of the relevant questionnaire were collected. Of these, 222 (66%) copies were used to conduct the final analysis; participants who did not have experience of a VR program and those who gave blank answers were excluded.

Instrument

Questionnaire Development

The self-report questionnaire comprised items on the perception of VR programs, VR program development requirements, and the general characteristics of the participants. The author first composed a draft questionnaire based on the literature review

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and further formed an expert group based on the criteria of Lynn [10] to verify content validity. The expert group comprised 5 professors from the nursing department who either lectured on CNS, such as fundamental nursing, or had experience in VR-related research. The expert group independently evaluated the content validity index (CVI) of the preliminary items. The content validity coefficients of each item (Item-CVI [I-CVI]) were measured using a 4-point scale; the responses ranged from 1 (“not necessary at all”) to 4 (“very necessary”). Regarding the expert opinions, items with an I-CVI of 0.80 or higher were selected, whereas those with an I-CVI less than 0.80 were removed from the questionnaire. Based on the expert opinions that some questions needed to be further subdivided, the questionnaire was modified to comprise 59 items. The draft questionnaire was then used in a preliminary survey targeting 10 nursing students. Based on their feedback, some phrases were modified in the final questionnaire.

Perception of VR Programs

The questionnaire on the perception of VR programs comprised 10 items, including items inquiring how much the individuals knew about the concept of a VR program, the necessity of introducing a VR program in the nursing department, and the need for developing VR programs. The answers ranged from 1 point (“strongly disagree”) to 5 points (“strongly agree”) and were scored on a 5-point Likert scale. In this study, Cronbach α was .78.

Needs Assessment for Developing VR Programs

In this research, the “needs” means the discrepancy between participants’ current status and future importance required to develop the VR program for CNS. Performance competence level (PCL), reflecting the current importance level, and required competence level (RCL), reflecting the priority for developing VR programs, were surveyed for 20 CNS suggested by the KABONE. Answers were given on a 5-point Likert scale, ranging from 1 (“strongly disagree”) to 5 (“strongly agree”). In this study, Cronbach α was .82.

General Characteristics

The questionnaire on the general characteristics of the participants comprised 9 items, including the total credits for the CNS, age, sex, etc.

Data Analysis

The collected data were coded and analyzed using SPSS statistics software (version 25.0; IBM Corp). The general characteristics of the participants were analyzed using descriptive statistics, such as frequencies and percentages, as well as means and SDs. To determine the priority of the demand for developing VR programs for CNS, the analysis method of Cho [9] was applied as follows.

First, the significance of the average difference between the PCL and RCL was analyzed using a 2-tailed *t* test.

Second, Borich priority was calculated to determine the priority of the development of VR programs of CNS [11]. The Borich priority formula is as follows:

RCL is each individual’s current importance level of CNS score, PCL is each individual’s importance level for developing VR programs of CNS score, is the average of the required level, and N is the total number of cases.

Third, priorities were visualized using the LFM. The items belonging to the first quadrant, higher than the average value of the RCL and PCL, were determined as priorities. The LFM is shown in Figure 1. The LFM is a method of visually deriving priorities using a coordinate plane by marking the RCL on the horizontal axis and the average difference between the RCL and PCL on the vertical axis [12]; the median value on the horizontal axis is the average RCL, and the median value on the vertical axis is the average difference between the RCL and PCL. Generally, the first quadrant is the high-discrepancy, high-importance (HH) quadrant, where the difference between the 2 levels and demand for development is higher than the average (Figure 1). The third quadrant is the low-discrepancy, low-importance (LL) quadrant, where the difference between the 2 levels and demand for development is lower than the average; hence, items in the LL quadrant are not considered development priorities. Although the LFM makes it easy to prioritize items in the first quadrant, there is a need to ascertain where the next-priority quadrant is. Moreover, it may be difficult to determine priorities even within the same quadrant [9].

Finally, both Borich priority and the LFM were combined to determine the highest priority. The LFM is a simple quadrant plot, but when used with the Borich formula, it has the advantage of comprehensively considering the current status and future importance of training needs and the discrepancy between the 2. Specifically, if 10 needs fall into the HH quadrant in the LFM, we checked whether those 10 needs are also ranked as the top 10 priorities by the Borich formula. If so, those needs were considered to have the highest priority.

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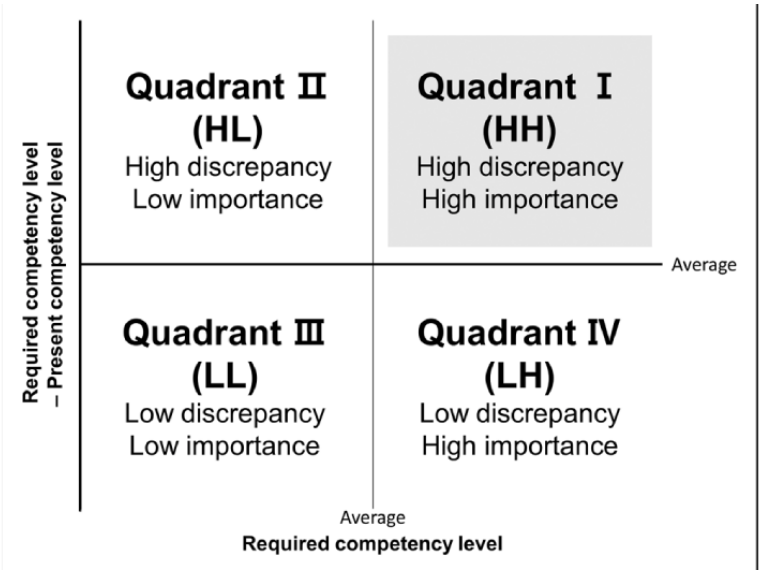
Figure 1. The Locus for Focus Model.



Recruitment and Informed Consent

A recruitment notice introducing the study, including the research purpose, ethics protocol, and survey URL, was posted on a social networking site frequently visited by nursing students. Students who wished to participate completed a web-based survey in Google Forms. The first question required participants to confirm their informed consent to take part in the study. The form advised participants that they could withdraw at any time and that their data would be used only for security maintenance and research purposes. No personal information, such as names and email addresses, was collected to ensure participants' anonymity.

Ethics Approval

This study was approved by the Institutional Review Board of Wonkwang University (approval WKIRB-202011-SB-078).

Results

Participant Characteristics

A total of 222 nursing students participated in the survey, among whom women were the majority (n=201, 90.5% vs men, n=21, 9.5%), with an average age of 23.3 (SD 3.33) years. Most participants (n=95, 42.8%) were third-year students. Regarding the contents of VR programs experienced in real life, games were the most common (42/308, 13.6%), followed by movies or dramas (39/308, 12.7%). Unlike experience in real life, only 27 (N=222, 12.2%) students experienced VR in university subjects, with nursing-related subjects being the most frequent (20/44, 45.5%; Table 1).

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Table 1. General characteristics of participants (n=222).

Characteristic	Value
Sex (n=222), n (%)	
Male	21 (9.5)
Female	201 (90.5)
Age (years), mean (SD)	23.3 (3.33)
Year of university (n=222), n (%)	
Second year	36 (16.2)
Third year	95 (42.8)
Fourth year	91 (41)
University location (n=222), n (%)	
Seoul capitol	50 (22.5)
Metropolitan city	60 (27)
Province	112 (50.5)
Nursing practice credits, mean (SD)	3.65 (1.5)
VR[a] experience contents (n=308, multiple responses), n (%)	
Game	42 (13.6)
Movie or drama	39 (12.7)
Education	34 (11)
Travel or sightseeing	34 (11)
Shopping	31 (10.1)
Sports	17 (5.5)
Concert	10 (3.2)
Others	1 (0.3)
VR experience during university curriculum (n=222), n (%)	
Yes	27 (12.2)
No	195 (87.8)
VR experience subjects at university (n=44, multiple responses), n (%)	
Nursing	20 (45.5)
Engineering	8 (18.2)
Media, architecture, or costume	5 (11.4)
Art or music	5 (11.4)
Pure science	3 (6.8)
History	3 (6.8)
English	0 (0)
Others	0 (0)

[a]VR: virtual reality.

Perception of VR

The overall perception of the VR program (calculated as the mean score for the 10 survey items) was 3.57 (SD 0.57), which was above average. Regarding the questionnaire items, the subjects showed the most positive response to the items indicating that the core nursing VR program would enhance clinical performance (mean 3.90, SD 0.98) and the quality of CNS (mean 3.90, SD 0.95). In contrast, the items “How much do you think you know about the concept of VR?”(mean 3.22, SD 0.90) and “Do you think VR products have become popular?” (mean 3.22, SD 0.92) had the lowest score but moderate-to-high levels of awareness (Table 2).

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Table 2. Perception of virtual reality (VR) programs (N=222).

No	Items	Score, mean (SD)
1	Do you think that VR products have become popular?	3.22 (0.92)
2	How much do you think you know about the concept of VR?	3.22 (0.90)
3	Do you think that the nursing department needs to introduce VR programs?	3.60 (0.90)
4	Do you think that it is necessary to develop a VR program for teaching CNS[a]?	3.75 (0.90)
5	Do you think that the CNS VR program will enhance clinical performance such as imparting technical skills?	3.90 (0.98)
6	Do you think that the CNS VR program will help improve critical thinking?	3.40 (1.06)
7	Do you think that the CNS VR program will help improve communication?	3.35 (1.06)
8	Do you think that the CNS VR program will help in decision-making?	3.58 (1.09)
9	Do you think that the CNS VR program will enhance the quality of CNS lectures?	3.90 (0.95)
10	Do you think that the CNS VR program can replace face-to-face CNS lecture?	3.25 (1.21)
	Total	3.57 (0.57)

[a]CNS: core nursing skills.

Priority of Demand for the Development of VR Programs for CNS: Results from the Borich Priority Formula

To find out the needs of nursing students for the development of the CNS VR program, the 2-tailed *t* test and Borich priority were calculated. The differences between the average PCL and RCL were considered statistically significant in the *t* test for all 20 CNS. As a result of calculating Borich priority, enema showed the highest demand for the development of a VR program (3.29), followed by administration of intramuscular (IM) injections (3.25) and tube feeding (2.91). In contrast, intravenous (IV) infusion (1.11), administration of oral medication (1.30), and administration of subcutaneous (SQ) injection (1.48) were considered the CNS with the lowest demand for the development of a VR program (Table 3).

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Table 3. Results of paired 2-tailed t test and the Borich needs assessment model for the demand of the development of virtual reality (VR) programs (N=222).

No	Core nursing skills	PCL[a], mean (SD)	RCL[b], mean (SD)	Mean difference, mean (SD)	*t* test (*df*=221)	*P* value	Borich	
							Needs	Rank
1	Vital sign	3.69 (1.08)	4.19 (0.97)	0.50 (1.42)	5.20	<.001	2.08	12
2	Administration of oral medication	3.64 (0.93)	3.97 (1.12)	0.33 (1.29)	3.79	<.001	1.30	19
3	Administration of IM[c] injection	3.73 (1.18)	4.45 (0.79)	0.73 (1.25)	8.69	<.001	3.25	2
4	Administration of SQ[d] injection	3.99 (0.97)	4.33 (0.98)	0.34 (1.31)	3.89	<.001	1.48	18
5	Administration of ID[e] injection	3.82 (1.09)	4.42 (0.87)	0.61 (1.27)	7.15	<.001	2.69	5
6	IV[f] infusion	4.00 (1.08)	4.27 (1.19)	0.26 (1.51)	2.58	.011	1.11	20
7	Blood transfusion	3.90 (10.6)	4.42 (0.84)	0.53 (1.15)	6.84	<.001	2.33	9
8	Tube feeding	3.73 (1.09)	4.39 (0.95)	0.66 (1.25)	7.91	<.001	2.91	3
9	Urinary catheterization	3.93 (0.97)	4.35 (0.93)	0.42 (1.11)	5.63	<.001	1.82	16
10	Foley catheterization	3.93 (1.08)	4.34 (1.06)	0.41 (1.32)	4.62	<.001	1.78	17
11	Enema	3.65 (1.05)	4.40 (0.88)	0.75 (1.10)	10.16	<.001	3.29	1
12	Preoperative care	3.68 (1.03)	4.19 (0.92)	0.51 (1.20)	6.38	<.001	2.15	11
13	Postoperative care	3.77 (1.07)	4.37 (0.86)	0.60 (1.16)	7.67	<.001	2.62	6
14	Admission care	3.50 (1.03)	3.97 (1.21)	0.47 (1.40)	5.04	<.001	1.88	14
15	Gowning and gloving technique	3.72 (1.01)	4.18 (1.01)	0.46 (1.25)	5.46	<.001	1.92	13
16	Pulse oximeter and EKG[g] monitoring	3.68 (1.06)	4.24 (0.98)	0.56 (1.27)	6.60	<.001	2.39	7
17	Supplying oxygen via nasal cannula	3.73 (1.06)	4.36 (0.93)	0.63 (1.16)	8.10	<.001	2.75	4
18	Endotracheal suction	3.80 (1.11)	4.34 (1.05)	0.54 (1.28)	6.30	<.001	2.34	8
19	Tracheostomy tube care	3.86 (1.04)	4.29 (1.06)	0.43 (1.23)	5.25	<.001	1.85	15
20	CPR[h] and using defibrillator	3.96 (1.10)	4.45 (0.80)	0.50 (1.17)	6.30	<.001	2.21	10

[a]PCL: performance competence level.
[b]RCL: required competence level.
[c]IM: Intramuscular.
[d]SQ: subcutaneous.
[e]ID: intradermal.
[f]IV: Intravenous.
[g]EKG: electrocardiogram.
[h]CPR: cardiopulmonary resuscitation.

Top-Priority Categories for the Demand for Developing VR Programs for CNS: Results From Combining Borich Priority and the LFM

In the analysis of the priority for the development of a VR program using the LFM, the average RCL for the development of a VR program for CNS was 4.30, and the average level of the difference between the RCL and PCL was 0.51. As a result of dividing the coordinate planes using these averages as an axis, 8 items such as IM injection, ID injection, blood transfusion, tube feeding, enema, postoperative care, supplying oxygen via nasal cannula, and endotracheal suction were included in the HH quadrant (Figure 2).

Finally, both Borich priority and the LFM were combined to determine the highest priority. In other words, any number of the 8 items of the first quadrant (HH) using the LFM and the 8 items of the Borich ranking priority could be selected. As a result, 7 items were included in the top priority for development, including IM injection, ID injection, tube feeding, enema, postoperative care, supplying oxygen via nasal cannula, and endotracheal suction (Table 4). All but 1 of the 7 items (supplying oxygen via nasal cannula) were found to correspond to a moderate or higher level of difficulty set by KABONE, and 2 of them (ID injection and endotracheal suction) were found to correspond to a high level of difficulty.

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Figure 2. Visualization of priority of the development needs of a virtual reality program using the Locus for Focus Model. C: core nursing skill; HH: high-discrepancy, high-importance; PCL: present competency level; RCL: required competency level.

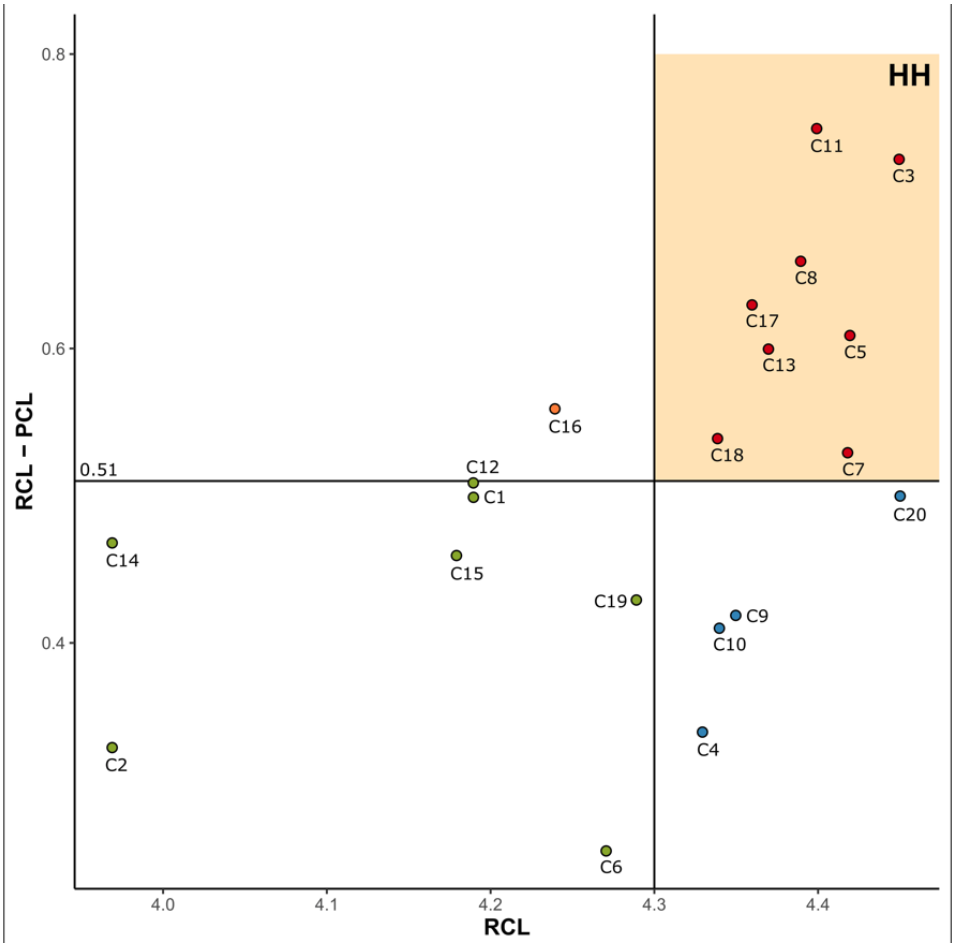

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Table 4. Top-priority developmental needs for core nursing skills according to Borich needs assessment model and the Locus for Focus Model (LFM).

No	Core nursing skill	Borich rank	LFM quadrant	Top priority
1	Vital sign	12	LL[a]	
2	Administration of oral medication	19	LL	
3	Administration of IM[b] injection	2	HH[c]	✓[d]
4	Administration of SQ[e] injection	18	LH[f]	
5	Administration of ID[g] injection	5	HH	✓
6	IV[h] infusion	20	LL	
7	Blood transfusion	9	HH	
8	Tube feeding	3	HH	✓
9	Urinary catheterization	16	LH	
10	Foley catheterization	17	LH	
11	Enema	1	HH	✓
12	Preoperative care	11	LL	
13	Postoperative care	6	HH	✓
14	Admission care	14	LL	
15	Gowning and gloving technique	13	LL	
16	Pulse oximeter and EKG[i] monitoring	7	HL[j]	
17	Supplying oxygen via nasal cannula	4	HH	✓
18	Endotracheal suction	8	HH	✓
19	Tracheostomy tube care	15	LL	
20	CPR[k] and using defibrillator	10	LH	

[a]LL: low discrepancy, low importance.
[b]IM: intramuscular.
[c]HH: high discrepancy, high importance.
[d]✓: indicates the highest priority for developing into virtual reality programs.
[e]SQ: subcutaneous.
[f]LH: low discrepancy, high importance.
[g]ID: intradermal.
[h]IV: intravenous.
[i]EKG: electrocardiogram.
[j]HL: high discrepancy, low importance.
[k]CPR: cardiopulmonary resuscitation.

Discussion

Principal Findings

The purpose of this study was to use the Borich priority formula and LFM to understand which CNS most require the development of VR programs to meet the needs of nursing students.

The study participants comprised 222 students in their second year or higher, who had taken courses on fundamental nursing or CNS and had experienced VR programs. Although 72.8% of the participants experienced VR programs in their daily lives, only 12.2% used them in the university curriculum. The participants showed the lowest score (mean 3.22, SD 0.90) for the questionnaire item regarding the concept of VR. This appeared to be consistent with the previous research results, which indicated that only 61.6% of students who had heard of VR or augmented reality (AR) before (99.7%) said they could accurately distinguish between VR and AR [13]. Nevertheless, the participants responded that VR programs for CNS would help enhance clinical performance (mean 3.90, SD 0.98), as well as the quality of CNS education (mean 3.90, SD 0.95), showing positive expectations for practical training using VR programs in the future. This was consistent with the results of previous related studies, which stated that VR- and AR-applied education would enhance learning and clinical performance [13]. In addition, the use of VR programs not only improves students' understanding and proficiency in CNS but also allows them to experience, in advance, how to respond to various patient reactions when directly performing CNS in real nursing

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situations [14]. Training using VR programs that provided repetitive training under the supervision of the educator increased the skill-retaining period compared with traditional one-time face-to-face training or self-practice in an open laboratory without appropriate feedback from the educator [15,16]. These prior research results are consistent with the results of this study, which indicate that education using VR programs will help improve clinical performance in hospitals in the future.

Based on the results of this study, the participants identified the differences between the PCL and RCL in developing VR programs for CNS. In other words, the PCL was statistically significantly lower than the RCL for all the items. This result means participants showed awareness of the need to develop VR programs when there is a difference between the PCL and RCL [17]. The top development priority items according to Borich needs formula included enema (3.29), administration of IM injection (3.25), and tube feeding (2.91). On the other hand, the lowest rankings were IV infusion (1.11), administration of oral medication [1.30], and administration of SQ injection [18]. In the coordinate plane using the LFM, the priority items for development (HH quadrant) totaled 8 items, including IM injection, ID injection, blood transfusion, tube feeding, etc. The KABONE classifies 20 CNS into higher (6 skills), middle (9 skills), and lower (5 skills) levels of difficulty. The LFM analysis revealed that 3 of 8 items in the HH quadrant (ID injection, blood transfusion, and endotracheal suction) corresponded to higher-difficulty CNS according to the KABONE. Additionally, 7 items in the LL quadrant (vital sign, administration of oral medication, IV infusion, preoperative care, admission care, gowning and gloving technique, and tracheostomy tube care) were not considered priority items for the development of a VR program, whereas 3 items (vital sign, oral medication, and admission care) in that quadrant were classified as lower difficulty according to the KABONE. In other words, the difficulty of CNS set by the KABONE and priority in the development of a VR program by the LFM according to the results of this study were consistent.

In the last step, the items and number of items in the HH quadrant of the LFM, as well as the same number of priority items according to the Borich needs assessment, were identified to determine the overlapping items in the 2 methods. As a result of the analysis, a total of 7 items, including IM injection, ID injection, tube feeding, enema, postoperative care, supplying oxygen via nasal cannula, and endotracheal suction, were found to be the top-priority items for the development of a VR program.

This result was similar with the items identified in previous studies, indicating that new graduate nurses and nursing students had the lowest confidence in the necessary skills for enemas, tracheostomy tube care, tube feeding, postoperative care, etc [18-23]. Additionally, nursing students chose tracheostomy tube care and enema as the CNS that they did not have the opportunity to practice in person or observe. This finding means that most of the clinical practice of nursing students was focused on noninvasive, safe, and simple skills that do not invade patient's privacy, involving low exposure of the patient's body. In other words, the participants were found to have selected invasive items with few opportunities for direct execution and observation during practical apprenticeship training, despite their close association with patient safety and importance, as CNS of high priority for the development of a VR program. This finding can also be confirmed in that most of the skills belonging to LL quadrant in the LFM, an area that is not considered for development priorities, are skills that can be delivered verbally rather than through direct contact with patients.

Previous related studies indicated that students who undergo CNS training through a VR program were able to minimize possible harm to patients when exposed to the actual clinical environment [24,25]. VR programs are designed to prevent the student from proceeding to the next step if they make mistakes related to patient safety or choose the wrong method; this may have contributed to the students improving their skills. Therefore, the development of VR programs for invasive CNS should be prioritized to reduce the possibility of the occurrence of errors during clinical practice and the fear of students to learn skills that can harm patients through repetitive practice of the nursing skills in a safe and realistic environment. CNS are mostly taught in a preparatory course before clinical practice. Nursing students, therefore, want a program that allows for effective practice of CNS as a preparatory course in school [26]. Moreover, most of the items that necessitate the development of VR programs show a low frequency of indirect experience in practical apprenticeship training and in-school simulation practice [22]. Accordingly, the reinforcement of skill learning through VR programs for these items appears to be necessary.

Education comprises 3 elements: the educator, student, and educational content. The "student" variable is considered the most important factor in determining the quality of educational performance. Students are the end consumers of all the content provided in the curriculum and are substantially influenced in terms of their career paths through the enhancement of their abilities and competencies. Therefore, it is essential to first analyze the needs of learners and configure the curriculum accordingly in the new, normal post–COVID-19 era. Particularly, in the field of nursing, where practical education occupies a large part of the curriculum, it is necessary to identify the needs of students for practical education and develop a curriculum that reflects them [26]. Post–COVID-19 education requires a paradigm shift. In other words, it is necessary to establish an on-demand form of education that reflects the diverse competencies and needs of students [1]. In this respect, this study's analysis of the demands for the development of VR programs for teaching CNS is important. In other words, it will be necessary to consider various approaches to teach the 20 CNS to further provide learner-centered personalized education, hence meeting the needs of students by applying traditional learning methods to the items that generate low-development demands and developing VR programs for items that generate high-development demands.

Limitations

This study has the following limitations. First, in terms of study participants and sampling, the survey was conducted on a website visited by many nursing students. Therefore, it was not

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possible to perform more precise sampling by region and year of university. This limits generalization in the interpretation and application of the research results. Therefore, there is need for future research to increase the possibility of generalization through sampling by region and year of university. Second, there is a need for further research according to demographic characteristics, such as how participants take relevant classes (face to face or remotely) or their exposure to clinical or VR training. Previous studies on confidence in CNS showed differences in difficulty and confidence depending on the general characteristics of the subjects. In other words, conducting research by considering the variables more comprehensively according to the demographic characteristics of participants, such as how they take CNS-related courses, will enable the development of more practical and systematic VR programs for teaching CNS, providing appropriate content for students in each year of university. Third, this study was conducted among nursing students. Therefore, there is a need to conduct studies with participants with various experiences, such as new nurses or preceptors. In other words, it will be possible to establish a continuous and virtuous cycle of learning that connects schools to hospitals and back to schools by examining the training methods and confidence in CNS for new nurses and reflecting these results back into the curriculum of the university.

Comparison With Prior Work

There are many studies on CNS, but there are no studies examining the needs of students following the development of CNS VR programs. As there are no studies similar to this study, it is difficult to compare its results with those of previous studies.

Conclusions

Nursing education is aimed at acquiring and integrating knowledge, attitudes, and skills to solve health problems through lectures and practice. CNS are practical skills that each individual nursing student must acquire through repeated practice before clinical practice, requiring self-directed learning capabilities. The analysis of the development demands and priorities for developing VR programs for CNS showed that nursing students generally asked for the development of VR programs for nursing skills that involved invasive procedures. The results of this study are intended to help various aspects of in-school practical education using VR programs in nursing departments, which are currently facing difficulties in teaching CNS on the web owing to COVID-19.

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Authors' Contributions

Both authors listed in this publication conducted the research. EJ and JL were responsible for study conception and design. JL collected the data. EJ and JL analyzed and interpreted the results. EJ and JL wrote the article. Both authors reviewed the results and approved the final version of the manuscript.

Conflicts of Interest

None declared.

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Abbreviations

AR: augmented reality
CNS: core nursing skills
CVI: content validity index
HH: high discrepancy, high importance
I-CVI: Item–content validity index
ID: intradermal
IM: intramuscular
IV: intravenous
KABONE: Korean Accreditation Board of Nursing Education
LFM: Locus for Focus Model
LL: low discrepancy, low importance
LNA: learning needs analysis
PCL: present competency level
RCL: required competency level

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SQ: subcutaneous
VR: virtual reality

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Original Paper

A Novel Scenario-Based, Mixed-Reality Platform for Training Nontechnical Skills of Battlefield First Aid: Prospective Interventional Study

Wenqiong Du[1], PhD; Xin Zhong[1], BA; Yijun Jia[1], PhD; Renqing Jiang[1], BA; Haoyang Yang[1], BA; Zhao Ye[1], BA; Zhaowen Zong[1], PhD

State Key Laboratory of Trauma, Burn and Combined Injury, Department for Combat Casualty Care Training, Training Base for Army Health Care, Army Medical University, Chongqing, China

Corresponding Author:
Zhaowen Zong, PhD
State Key Laboratory of Trauma, Burn and Combined Injury
Department for Combat Casualty Care Training, Training Base for Army Health Care
Army Medical University
30 Gaotanyan St
Shapingba District
Chongqing, 400038
China
Phone: 86 138 8350 6677
Fax: 86 23 8771873
Email: zongzhaowen@163.com

Abstract

Background: Although battlefield first aid (BFA) training shares many common features with civilian training, such as the need to address technical skills and nontechnical skills (NTSs), it is more highly scenario-dependent. Studies into extended reality show clear benefits in medical training; however, the training effects of extended reality on NTSs, including teamwork and decision-making in BFA, have not been fully proven.

Objective: The current study aimed to create and test a scenario-based, mixed-reality platform suitable for training NTSs in BFA.

Methods: First, using next-generation modeling technology and an animation synchronization system, a 10-person offensive battle drill was established. Decision-making training software addressing basic principles of tactical combat casualty care was constructed and integrated into the scenarios with Unreal Engine 4 (Epic Games). Large-space teamwork and virtual interaction systems that made sense in the proposed platform were developed. Unreal Engine 4 and software engineering technology were used to combine modules to establish a mixed-reality BFA training platform. A total of 20 Grade 4 medical students were recruited to accept BFA training with the platform. Pretraining and posttraining tests were carried out in 2 forms to evaluate the training effectiveness: one was knowledge acquisition regarding the NTS and the other was a real-world, scenario-based test. In addition, the students were asked to rate their agreement with a series of survey items on a 5-point Likert scale.

Results: A battlefield geographic environment, tactical scenarios, scenario-based decision software, large-space teamwork, and virtual interaction system modules were successfully developed and combined to establish the mixed-reality training platform for BFA. The posttraining score of the students' knowledge acquisition was significantly higher than that of pretraining ($t=-12.114$; $P\leq.001$). Furthermore, the NTS score and the total score that the students obtained in the real-world test were significantly higher than those before training ($t=-17.756$ and $t=-21.354$, respectively; $P\leq.001$). However, there was no significant difference between the scores of technical skills that the students obtained before and after training. A posttraining survey revealed that the students found the platform helpful in improving NTSs for BFA, and they were confident in applying BFA skills after training. However, most trainees thought that the platform was not helpful for improving the technical skills of BFA, and 45% (9/20) of the trainees were not satisfied with the simulation effect.

Conclusions: A scenario-based, mixed-reality platform was constructed in this study. In this platform, interaction of the movement of multiple players in a large space and the interaction of decision-making by the trainees between the real world and the virtual world were accomplished. The platform could improve the NTSs of BFA. Future works, including improvement of the simulation

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effects and development of a training platform that could effectively improve both the technical skills and NTSs of BFA, will be carried out.

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KEYWORDS

mixed reality; decision-making; team work; battlefield first aid; nontechnical skills; training; next-generation modeling; virtual reality; medical education

Introduction

Nontechnical skills (NTSs) are defined as "cognitive, social, and personal resource skills that complement technical skills, and contribute to safe and efficient task performance," and decision-making and team cooperation are the 2 most important parts of NTSs in medicine [1,2]. Given that there is accumulating evidence for the positive impact of improved NTSs on patient outcomes [2], NTSs have gained much attention in medical training in recent years. Training for battlefield first aid (BFA) is a special branch of medical training. NTSs play an important role in BFA because the BFA providers face hostile fire when they rescue the injured. Decisions should be made and techniques should be chosen based on different tactical combat backgrounds [3,4]. In addition, the commander needs to synchronously organize combat and first aid, which requires close team cooperation compared with civilian first aid. Thus, NTSs should be addressed during BFA training.

There are currently several types of training methods for first aid, including lecture, practice on animal tissues, high-fidelity training simulators, and virtual reality (VR). Each method has its advantages and disadvantages [5]. Lectures are conducive to imparting knowledge, but not conducive to training first-aid skills. The use of live animal tissues, such as the chest wall or trachea covering from pigs, is suitable for training invasive first-aid skills such as needle decompression and cricothyrotomy; however, it is difficult to integrate the actual exercise into a tactical context [6]. High-fidelity mannequins can simulate various emergent conditions such as bleeding and airway obstruction, and they have been proven effective in improving trainees' first-aid abilities. However, the limitations of these mannequins include their high cost, requirement of experienced operators, and poor integration into an actual tactical training environment [5,7]. In recent years, extended reality (XR), VR, augmented reality (AR), and mixed reality (MR), have been widely used in medical education, training, surgical planning, and the telementoring of complicated operations [8-10]. In addition, it has also been shown that VR, AR, and MR can improve the training effect of first-aid skills [11-13]. For example, Stone et al [13] developed an MR-based training platform for The UK Emergency Medical Team, which could blend the real-world objects of training relevance with VR reconstructions of operational contexts. Furthermore, AR has been shown to increase the accuracy and performance of medical students or medics in treating pneumothorax, airway management, and cardiopulmonary resuscitation training [8,11,12]. However, these XR-based methods have not been fully proven to effectively improve first-aid NTSs, especially the NTSs in BFA. The aim of this study was to create and test a tactical scenario-based, MR platform suitable for training the NTSs of BFA.

Methods

Ethical Considerations

All procedures were approved by the Ethics Committee of the Army Medical University of China PLA (approval #AMUWEC2020172) and were performed in accordance with the relevant regulations of the Ethics Committee of the Army Medical University of China PLA, China.

Construction of a High-fidelity Platform for Training BFA

Establishment of Simulated Tactical Scenarios

To address first-aid skill training in tactical background and team cooperation in first aid, the training scenario was designed as a 10-person–based offensive battle drill conducted in mountainous terrain. One author with expertise in tactical command (ZY) was responsible for designing the training scenario. Briefly, the trained group selected a team leader. The trainees were then asked to siege a hill that was guarded by 3 soldiers. During the siege procedure, 2 trainees were programmed to be injured by hostile fire, and the team leader was asked to organize the hill-siege attack as well as the care of the injured personnel; the whole team was required to make correct decisions based on the tactical situation, cooperate, and complete the tactical task and BFA.

Based on the designed scenario, a 3D computer modeling of the scenario was established. First, high-precision models of soldiers, combat weapons, and armored vehicles were established by next-generation modeling technology. Second, animation of these objects and battle scenes were made based on the designed running variables and conditions. Third, the positions of the soldiers' head in the real world were obtained by the simultaneous localization and mapping (SLAM) technique built into the VR glasses (head-mounted displays, HTC Vive Pro 2.0, High Technology Computer Corporation); the positions of the soldiers' trunk in the real world were obtained by a home-made smart vest that contained location sensors (Chongqing High Tech Corporation); and the positions and movements of the simulated guns in the real world were captured by a built-in 9-axis sensor (Chongqing High Tech Corporation). These positions and movements were analyzed by an artificial intelligence system, and then an animation was generated in the virtual world. The actions of the 3 defending soldiers in the virtual world were trained by the artificial intelligence system in accordance with the script for action

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control. In this way, the interaction of the soldiers' actions between the real world and the virtual world was accomplished.

3D Modeling of the Simulated Battlefield Geographic Environment

As mentioned previously, the training scenario in this study was designed as an offensive battle taking place in a mountain area. Thus, several pictures of mountain areas were taken and used for the construction of the simulated battlefield geographic environment.

The 3D modeling of the geographical environment was divided into 5 layers: a terrain layer, surface layer, vegetation layer, building layer, and environment layer. The terrain layer was generated and restored by high-precision low-surface restoration technology and a 3D terrain-generation algorithm based on contour synthesis. On the basis of sampling and analyzing the surface material, the surface layer was constructed by composite material ball technology. The vegetation layer and the building layer were constructed by next-generation modeling technology in accordance with the simulated battlefield vegetation situation, training task, and imaginary enemy target situation. The environment layer simulated the real ambient light and weather corresponding to different combat times according to the training content.

Construction of Software for Training of Decision-Making

To train the decision-making ability of the trainees, a decision tree was constructed. One author (ZZ), who had undergone tactical combat casualty care training in Ulm Hospital, Germany, was responsible for the construction of the decision tree. Key aspects of the basic principles of tactical combat casualty care, decision-making, injury state assessment, selection of appropriate first-aid tools, selection of appropriate first-aid skills, and important steps or details of each first-aid skill were listed. In total, 20 items were listed. Examples include "return fire first under hostile fire," and "only apply tourniquet under hostile fire threat but no other procedures such as wound dressing for wounds with minor bleeding" [3,4]. The whole study group (the authors) consisted of the members of the Department of Training for Combat Casualty Care. There were 6 males and 1 female, with an average age of 34.6 (SD 5.28) years. We discussed and decided which items should ultimately be listed. Once the list had been completed, 1 question and 4 options were given for each item (Multimedia Appendix 1). The validity of the content was then checked by 6 trauma surgeons from Army Medical University based on questionnaires. These trauma surgeons were randomly selected from the Academic Committee on Trauma Care, Army Medical University. They were all men, with an average age of 52.3 (SD 6.47) years. These expert questionnaires were employed to evaluate the scientificity and feasibility of the testing standard. For the evaluation of scientificity, scores of 1, 3, 5, 7, and 9 indicated that the scientificity was very low, low, fair, high, and very high, respectively; for the evaluation of feasibility, scores of 1, 3, 5, 7, and 9 indicated that the testing standard was nonfeasible, fairly nonfeasible, feasible, fairly feasible, and highly feasible, respectively [14].

Unreal Engine 4 is a product of Epic Games, a top gaming company in the world [15,16]. It is one of the most widely used and sophisticated unreal engines at present. After continuous improvement, in addition to game development, it has also been used to perform film and television production, architectural design, car model building, urban planning, and factory assembly line simulation [16,17]. It provides a large number of core technologies needed by software developers, including the making of 3D game scenes, visual language, and C++ language. Blueprint is the visual language in Unreal Engine 4. It creates all kinds of executable processes in the form of "nodes" in advance, and then it can be easily programmed by the dragging of the mouse cursor to arrange and connect them. In this study, the constructed decision tree was visualized with the blueprint tool of Unreal Engine 4. An HTC Controller (HTC Vive Pro, High Technology Computer Corporation) was used by the participants to make choices in the virtual world.

Construction of a Mobile, Large-Space, Team Collaboration and Virtual Interaction System

We used the SLAM skills [17,18] and spatial anchoring techniques to develop a large-space, multiplayer interaction between the real and the virtual worlds. Briefly, based on the virtual battlefield geographic environment established previously, a zero point was set at the center point in the virtual map, and the coordinates of the zero point were set as (0, 0, 0). According to the size of the training site, the coordinates of the training site in real world were then located. The real-world and virtual-world zero points were used for spatial anchoring.

During the drill, the starting coordinate was set as the birth point of the character in the virtual world. For example, if the birth position of the character's virtual world was in the northeast coordinates (−250000, −250000, 0), then the real-world zero point was used for the spatial anchoring coordinates. When the character moved in the real world, the absolute motion coordinates of the virtual world could be obtained by the relative displacement between the dynamic coordinates and the spatial anchoring coordinates. The accurate dynamic coordinate relationship between the physical space and the virtual space was obtained by calculating the relative displacement through the spatial anchoring transformation. Based on the previous accurate coordinates of space anchoring, the world zeros (0, 0, 0) of multiple persons in the same physical real world were set at 1 point through the site calibration function of the positioning VR equipment, ensuring the consistency of the relative coordinates of multiple persons moving in the physical system and the relative position of the virtual world after anchoring. The relative motion of each person was transformed through the fixed anchor point and the virtual world patriarchal coordinate system, and the absolute position coordinates obtained were sent to each client in the form of a server network broadcast. After the client received the coordinates and unique information of different people, the picture was rendered through the 3D engine, and the reality was displayed in the VR glasses. In this way, the absolute coordinates of the virtual world could be compatible and synchronized in a large mobile space.

Once these separated modules had been constructed, Unreal Engine 4 and software engineering technology were used to

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combine these modules together to establish the high-fidelity training platform for BFA.

Training Process and Testing Process

The study was designed as a randomized trial comparing the results of a pretraining test and a posttraining test. None of the recruited individuals had previously received any kind of training related to BFA. A total of 20 Grade 4 medical students from Army Medical University were recruited as trainees and were divided into 2 teams. There were 14 boys and 6 girls, with an average age of 20.6 (SD 1.28) years. The VR training was based on the basic principle of simulation-based training: an introduction and MR familiarization phase (30 minutes), a training phase (120 minutes), and then a debriefing phase (20 minutes) [19]. Exclusion and discontinuation criteria for the participants were the presence of VR sickness symptoms such as discomfort, headache, or nausea [19,20]. Ten rounds of training were conducted for each team to ensure that each of the students was able to experience different roles (team leader, team members responsible for fighting, team members responsible for first aid, and the simulated casualty).

Pretraining and posttraining tests were carried out in 2 forms: one form was the knowledge acquisition regarding the NTSs [19,21], and another form was a real-world, scenario-based test [5]. Scores of knowledge acquisition regarding the NTSs of BFA were collected [19,21]. One hour before training and one hour after training, the students were asked to take a knowledge acquisition test. The content of knowledge test was the same as the aforementioned decision-making test (Multimedia Appendix 1), and the difference between the pretraining and posttraining test was the scrambled order of questions and answers [21]. A higher score corresponded to a higher level of knowledge [19].

One day before the training and two hours after the training, the real-world, scenario-based test was performed [5]. In the real-world, scenario-based test, the scenario was similar to the tactical scenario used to establish the platform in the current study. The main difference was that 2 simulators (Trauma HAL S3040.100, Gaumard) were placed in the offensive route, serving as simulated injured personnel. The students were asked to fulfill the task and rescue the simulated casualties synchronously. The test standard for the real-world, scenario-based test was as previously reported but with small modifications [5]. The modified test standard consisted of 2 parts: NTSs (40 points) and technical skills (60 points). The total score of the test was 100 points (Multimedia Appendix 2). Total score and scores of each part were recorded and used for statistical evaluation.

Posttest Survey

After the training, the trainees were asked to indicate their agreement with a series of survey items on a 5-point Likert scale (1=fully disagree, 2=disagree, 3=neutral, 4=agree, 5=fully agree) [22]. The research measures and questions are shown in Table 1.

Table 1. Measures and questions of posttraining survey.

Research measures	Questions
Confidence	1. I feel confident in applying my BFA[a] skills quickly and correctly after training.
Helpfulness and simulation effect	2. I feel the simulation training approach was more efficient in improving technical first aid skills than the traditional approach.
	3. The simulation effects of the battlefield geographic environment and battle scenario are very real.
	4. I thought the platform was helpful in improving team cooperation.
	5. The training platform was helpful in improving decision-making for first aid.

[a]BFA: battle-field first aid.

Statistical Analysis

All data are expressed as the mean and SE. SPSS 11.0 (IBM Corporation) was used to analyze the results. *t* tests were used to compare the pretraining and posttraining scores. The CI was set at 95% (95% CI). A value of $P<.05$ was considered significant.

Results

The Constructed MR platform

Based on the designed scenario (ie, a 10-person–based offensive battle drill conducted in mountainous terrain), the battlefield geographic environment and tactical scenarios were successfully developed. Figure 1 is an exemplary picture of the constructed battlefield geographic environment and Figure 2 is an exemplary picture of the constructed tactical scenarios.

A scenario-based decision tree was established; dialog boxes were created focusing on the key issues of injury assessment, decision-making as to which first-aid equipment should be selected, and decision-making as to whether return fire should be performed first or casualty care should be performed first. The scientific score was 8.47 (SE 1.15), and the feasibility score was 8.26 (SE 1.13). These results revealed that the experts agreed with our determined decision-making questions. A total of 20 dialog boxes were constructed, covering the key components of the scenario-based first aid (Multimedia Appendix 1).

In each dialog box, several options were offered for each question, and the trainees were asked to select the right one(s) during training or testing. In the training model, if a wrong choice was made, the procedure returned to the previous step until the right answer was selected; in the test model, if a wrong choice was made, the procedure continued according to the choice. Figure 3 shows an exemplary dialogue box: when a soldier demonstrated shortness of breath, increased breath frequency (30-40/minute), and laborious breath due to facial injury, the trainees were asked to select one answer out of four

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options: (1) airway obstruction, (2) open pneumothorax, (3) tension pneumothorax, and (4) traumatic brain injury (Figure 3). In the training model, if a wrong choice was made, the procedure returned to the previous step until the right answer was selected. In contrast, in the test model, if a wrong choice was made, the procedure continued, but the corresponding points were deducted.

A high-fidelity training platform for BFA was constructed by combining all the modules developed in the aforementioned step by Unreal Engine 4 and software engineering technology. The platform provided the whole-process experience of fighting against the enemy, taking casualties, conducting first aid for the casualties, and treating and completing the tactical tasks under the tactical background. By using spatial anchor sharing technology and an anchoring modification algorithm, the aims of team cooperation and MR (interaction between the visual world and the real world) were achieved. Figure 4 is an exemplary picture demonstrating the interaction between the real world and the virtual world.

Figure 1. Exemplary picture of the constructed geographic environment.

Figure 2. Exemplary picture of the constructed tactical scenarios.

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Figure 3. Screen capture of an exemplary dialog box for training to make a correct injury state assessment.

Figure 4. Exemplary picture showing the interaction between the real world and the virtual world.

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The Constructed Platform Was Helpful in Improving the NTSs of BFA

The students were divided into 2 teams to undergo training with the MR platform. During the training, the students moved freely, and they could cooperate with each other during the training. The leaders were in charge of the whole training process, making decisions and leading the teams to complete the mission (Multimedia Appendix 3). No student reported simulator-related sickness, such as discomfort, headache, or nausea.

The score that the students obtained in the knowledge acquisition test after the training was 17.35 (SE 1.35), which was significantly higher than that before training (t=−12.114; $P \leq .001$). In the real-world, scenario-based test, the NTS score that the students obtained after the training was 30.5 (SE 2.67), which was significantly higher than that before training (22.1, SE 5.34; t=−17.756; $P \leq .001$). In addition, the total score that the students obtained after the training was significantly higher than that before training (pretraining: 77.7, SE 3.17; posttraining: 66.45, SE 2.58; t=−21.354; $P \leq .001$). However, there was no significant difference between the scores of technical skills that the students obtained before and after the training ($P=.69$). These data indicated that the constructed platform was helpful for improving the NTSs of BFA but was not helpful for improving the technical skills of BFA.

Posttraining Survey

For question 1, students gave a mean score of 4.2, and most of the 20 students (n=18, 90%) felt confident in applying BFA skills quickly after training. For question 2, students gave a mean score of 2.3, and 65% (n=13) of the students disagreed and 30% (n=6) of the students were neutral regarding the following statement: “I feel the simulation training approach was more efficient in improving technical first-aid skills than the traditional approach.”

Moreover, 35% (7/20) of the participants disagreed and 40% (8/20) of the participants agreed with the following statement: “The simulation effect of the battlefield geographic environment and battle scenario is very real.” This indicated that the simulation effect of the constructed platform needed to be further improved.

For question 4, students gave a mean score of 4.4, and most students (18/20, 90%) thought the platform was helpful in improving team cooperation. For question 5, students gave a mean score of 4.75, and all of the participants (20/20, 100%) thought that the training platform was helpful in improving decision-making for first aid.

Discussion

Principal Findings

This study established a novel, MR platform that met the need for scenario-dependent decision-making and teamwork in the training field of combat first aid. First, a 10-person–based offensive battle taking place in a mountain area was designed as a tactical scenario; on that basis, simulated tactical scenarios and a battlefield geographic environment were established by next-generation modeling technology and an animation synchronization system. This enabled us to train first-aid skills in a tactical background. Second, decision-making training software addressing basic principles of tactical combat casualty care was constructed, making decision-making training possible. Third, a large-space team cooperation and virtual interaction system suitable for the simulation training system environment was developed, making teamwork training possible. Comparison of the performance of the pretraining and the posttraining tests showed that the platform constructed in this study was helpful in improving the NTSs of BFA. Furthermore, the posttest survey revealed that the students agreed that the platform was helpful in improving team cooperation and decision-making for first aid, and they were more confident in applying BFA skills after the training. However, most trainees thought that the platform was not helpful in improving technical skills in first aid, and 45% (9/20) of the trainees were not satisfied with the simulation effect of the battlefield geographic environment and battle scenario.

Comparison to Prior Work

High-level NTSs are of paramount significance for safe and effective medical care, especially in first aid, where the time for making decisions and taking measures is short. In recent years, behavior marker systems, first-person perspective video, and high-fidelity simulators have been shown to be effective in improving the NTS performance of first aid [2,23,24]. To the best of our knowledge, however, there are no XR-based simulators specifically focusing on the training of NTSs for first aid, and the current study is the first to focus on the training of BFA NTSs. The existing XR-based simulators reported in the literature mainly focused on single-skill training or on making the trainees familiar with the environments, but NTSs including decision-making and teamwork of first aid have seldom been addressed [20,25]. In addition, training NTSs of first aid using XR-based simulators is considered technically difficult [13,19,26].

A multiplayer design within the XR environment is thought to be able to offer a chance to rotate through different team roles, supporting an active and immersive learning experience with the potential to equip the learners with the crucial teamwork skills required for medical care [25]. Chheang et al [27] established anesthesia simulation software and laparoscopic simulation software that were combined within a multiuser VR environment; the interaction of multiplayers could be fulfilled in the virtual world. It was revealed that the multiuser-based software could improve problem-based communication during surgery. Krishnappa et al [28] developed a multiplayer interaction platform using VR augmented with eye-tracking technology, making children with autism spectrum disorder practice gaze sharing and gaze following in a team possible [28]. In our study, SLAM skills along with spatial anchoring techniques were used to make the movement and cooperation among 10 people possible. In addition, the interaction between the real world and the virtual world was accomplished. To the best of our knowledge, this is the first paper of its kind in the field of first-aid training. The multiplayer experience and the interaction between the real world and the virtual world are helpful for the improvement of team work [2].

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There is accumulating evidence showing the effectiveness of an XR-based simulator in improving medical skills; however, the underlying mechanisms for the effectiveness are controversial. Many factors, including the quality of the animation in XR, the additional physical stimuli, and visually induced motion sickness, are considered to affect the training effectiveness through attractiveness, motivation, or goal-oriented training procedures. Checa et al [29] found that immersive VR environments could enhance autonomous learning compared with a conventional lecture or the same serious game on a desktop computer and that novelty might play a role in the improved training effectiveness. In a study comparing the effects of tablet-based and VR-based serious gaming modules for basic life support training on learning outcomes, Aksoy et al [21] found that motivation by VR contributed to enhanced learning outcome [21]. In this study, 45% (9/20) of the trainees were not satisfied with the simulation effect of the battlefield geographic environment and battle scenario; however, the platform was able to effectively improve NTSs of BFA. Thus, we postulated that the improved NTSs might not be caused by the attractiveness of the simulated battlefield geographic environment and battle scenario; instead, we believe that the team work and decision-making–oriented design (ie, the decision tree incorporated in the software and the team cooperation design in the software) contributed to the improved NTSs.

Strengths and Limitations

This study has several strengths. To our knowledge, this is the first MR-based platform for training NTSs in BFA, and the training effectiveness was satisfactory. In addition, the interaction of 10 persons in a large space between the real world and the virtual world was accomplished for the first time in the field of first-aid training.

This study also has some limitations. First, the simulation effect of the geographic environment and battle scenario need to be greatly improved. The posttraining survey revealed that the students were not highly satisfied with the simulation effect. This quality of the simulated battlefield geographic environment and battle scenario probably negatively affected the training effectiveness. The reason for the relatively low quality of simulation is related to the limited budget. Thus, in the future, efforts will be made to further improve the simulation effect when enough funding is available. Second, invasive first-aid techniques and technical first-aid skills could not be trained in the current platform, and this had a negative impact on the training effectiveness as confirmed by the finding that training with the platform did not improve the score of technical skills in the real-world test. AR has been shown to be beneficial for invasive first-aid techniques training; thus, the combination of techniques used in the current study with XR techniques might be a good option to address more challenges faced by BFA training.

Future Directions

Given the strengths and limitations of this study, a training platform that could effectively improve both the technical skills and NTSs of BFA will be developed. In addition, efforts will be made to improve the simulation effect of the battlefield geographic environment and battle scenario; following this, the role of the improved quality of simulation in training effectiveness will be investigated with the current platform as a control.

Conclusions

A novel scenario-based, MR platform was constructed in this study. In this platform, interaction of the movement of 10 people in a large space between the real world and the virtual world was accomplished with SLAM skills along with spatial anchoring techniques, and the interaction of decision-making by the trainee between the real world and the virtual world was fulfilled by the HTC Controller. The constructed platform could improve the NTSs (ie, team work and decision-making) of BFA. Future works, including improvement of the simulation effects and development a training platform that could effectively improve both the technical skills and NTSs of BFA, will be carried out.

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Data Availability

The data sets generated during and/or analyzed during the current study are available from the corresponding author (ZZ) on reasonable request.

Authors' Contributions

WD developed the software; XZ developed the 3D models; YJ and RJ conducted training and testing and the application of the survey; HY performed the collection, analysis, and interpretation of data; ZY designed the training scenario; and ZZ was responsible for the construction of the decision tree, conceptualization, original drafting, and funding acquisition.

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Conflicts of Interest

None declared.

Multimedia Appendix 1
The list of the 20 multiple-choice questions for assessing the knowledge of decision-making.
[DOC File , 59 KB - games_v10i4e40727_app1.doc]

Multimedia Appendix 2
Testing standards used in the study.
[DOCX File , 18 KB - games_v10i4e40727_app2.docx]

Multimedia Appendix 3
Video demonstrating the training process.
[AVI File , 30983 KB - games_v10i4e40727_app3.avi]

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Abbreviations

AR: augmented reality
BFA: battlefield first aid
MR: mixed reality
NTS: nontechnical skill
SLAM: simultaneous localization and mapping
VR: virtual reality
XR: extended reality

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Original Paper

Teamwork Training With a Multiplayer Game in Health Care: Content Analysis of the Teamwork Principles Applied

Lara van Peppen[1,2*], PhD; Tjitske J E Faber[1,3*], MD; Vicki Erasmus[4], PhD; Mary E W Dankbaar[1*], PhD

[1]Institute of Medical Education Research Rotterdam, Erasmus University Medical Center, Rotterdam, Netherlands
[2]Learning and Innovation Center, Avans University of Applied Sciences, Breda, Netherlands
[3]Anesthesiologie, Pijn en Palliatieve Geneeskunde, Radboud Universitair Medisch Centrum, Nijmegen, Netherlands
[4]Implementation Research and Interprofessional Education, Erasmus University Medical Center, Rotterdam, Netherlands
[*]these authors contributed equally

Corresponding Author:
Tjitske J E Faber, MD
Anesthesiologie, Pijn en Palliatieve Geneeskunde
Radboud Universitair Medisch Centrum
Huispost 717, Route 714
PO Box 9101
Nijmegen, 6500 HB
Netherlands
Phone: 31 243614406
Email: Tjitske.Faber@radboudumc.nl

Abstract

Background: In health care, teamwork skills are critical for patient safety; therefore, great emphasis is placed on training these skills. Given that training is increasingly designed in a blended way, serious games may offer an efficient method of preparing face-to-face simulation training of these procedural skills.

Objective: This study aimed to investigate the teamwork principles that were used during gameplay by medical students and teamwork experts. Findings can improve our understanding of the potential of serious games for training these complex skills.

Methods: We investigated a web-based multiplayer game designed for training students' interprofessional teamwork skills. During gameplay, 4 players in different roles (physician, nurse, medical student, and student nurse) had to share information, prioritize tasks, and decide on next steps to take in web-based patient scenarios, using one-to-one and team chats. We performed a qualitative study (content analysis) on these chats with 144 fifth-year medical students and 24 health care teamwork experts (as a benchmark study) playing the game in groups of 4. Game chat data from 2 scenarios were analyzed. For the analysis, a deductive approach was used, starting with a conceptual framework based on Crew Resource Management principles, including shared situational awareness, decision-making, communication, team management, and debriefing.

Results: Results showed that most teamwork principles were used during gameplay: shared situational awareness, decision-making (eg, re-evaluation), communication (eg, closed loop), and team management (eg, distributing the workload). Among students, these principles were often used on a basic level. Among experts, teamwork principles were used with more open forms of speak up and more justification of decisions. Some specific Crew Resource Management principles were less observed among both groups, for example, prevention of fixation errors and use of cognitive aids. Both groups showed relatively superficial debriefing reflections.

Conclusions: Playing a multiplayer game for interprofessional teamwork appears to facilitate the application of teamwork principles by students in all important teamwork domains on a basic level. Expert players applied similar teamwork principles on a moderately high complexity level. Some teamwork principles were less observed among both students and expert groups, probably owing to the artifacts of the game environment (eg, chatting instead of talking). A multiplayer game for teamwork training can elicit the application of important, basic teamwork principles, both among novices and experts, and provides them with a flexible, accessible, and engaging learning environment. This may create time for exercising more complex skills during face-to-face training.

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KEYWORDS

teamwork; skills training; serious games; multiplayer game; medical students; content-analysis; health care; interprofessional teamwork

Introduction

Background

Across the globe, in high-stakes environments (such as aviation, nuclear power industries, and health care), teams work together to prevent harm. A team may be defined as "two or more persons with a common goal that requires interdependence and adaptive functioning" [1]. Teams may exist offline and on the web, including groups of individuals in different locations brought together by technology to accomplish a common goal or task [2]. For the team to achieve its goals, team members must perform both taskwork (meaning specific work-related activities) and teamwork, including sharing knowledge, coordinating behaviors, and trusting one another [3]. Studies in a variety of fields have established the benefits of both teamwork in itself [4] and training in team-based skills such as interdependent collaboration, communication, and shared decision-making [5,6].

In health care, many adverse events are associated with systematic issues and human error [7], such as problems in communication and lack of leadership [8,9]. One of the challenges in medical practice is that health care professionals perform interdependent tasks, with different roles and responsibilities, sharing the common goals of quality and safety in care. Especially in complex and acute emergency situations, environmental and patient conditions can easily alter judgments and affect both individual and team decision-making [10]. To successfully navigate such situations, good communication and cooperation are essential. However, in such situations, increased stress levels can disrupt good communication and cooperation. It becomes more challenging for team members to extract relevant information from other team members and individuals, communicate this information, and make joint decisions. Providing good and safe patient care requires more than medical knowledge and technical skills. Given the interdisciplinary nature of the work and the necessity for cooperation among health care professionals, teamwork is equally essential [9,11]. To reduce risks in medical practice, health care professionals should be equipped with the skills needed to effectively operate in dynamic safety-critical situations [12]. In other words, they require the skills needed to build and maintain adequate *situational awareness* in complex, dynamic, and high-risk situations. Therefore, training medical students in teamwork has received increased attention in the past decade, and teamwork principles are being introduced into several medical school curricula [6,13-17].

Team training encompasses a broad range of strategies, most commonly targeting communication, situational awareness, leadership, role clarity, and coordination [6]. In health care, the most commonly used type of training is Crew Resource Management (CRM) [18-20]. CRM is adopted from studies on aviation teams [21] and is currently used in many high-risk domains to train professionals. CRM includes team training, simulation, and interactive group debriefings. The main purpose of CRM is to teach professionals about the limitations of human performance and foster their understanding of cognitive errors and impact of stressors on decision-making processes. Teamwork skills being trained following CRM principles include, for instance, communicating, exerting leadership, anticipating and planning, managing workload distribution, and re-evaluating actions [22]. It is important to note that a shared framework for all CRM principles is missing [19] and that there is no universal CRM training program—organizations customize their CRM training to best suit their individual needs.

Training of Teamwork Skills

Teamwork skills are generally taught face-to-face, with a group in a simulation setting. Simulation-based education allows students to acquire new knowledge and skills in an environment that more or less resembles the future work situation and allows for live interaction between the team members. However, such training is cost intensive. To use time and resources more efficiently, many education systems shifted away from traditional face-to-face classes to blended learning—a combination of web-based instruction and face-to-face classes [23]. In a blended design, web-based learning is often implemented before face-to-face classes to create knowledge and skills on a basic level; face-to-face time is used to train skills on a high level and provide and process feedback [24]. Implementing blended learning can bring about a shift toward a more active approach to learning that focuses on the individual student [25,26]. Students have more control over their learning process and can adapt learning activities to their own needs and preferences [27]. For example, they can work at their own pace, relearn specific parts of the material, and choose when to learn. Numerous studies have shown that blended learning is at least as effective for the acquisition of knowledge and skills compared with traditional learning and that students are equally motivated to learn [24,28-32].

Web-based learning environments (such as e-learning modules or simulation programs) have proven to be valuable tools for developing and refining skills [29,33]. Web-based simulation training allows students to acquire new knowledge and skills in an environment that more or less resembles their future work situation. The use of web-based patients (ie, computerized clinical case simulations) as a learning tool is associated with enhanced cognitive clinical skills [34]. In addition, the use of technology-enhanced simulation training is consistently associated with large effects on learning outcomes for knowledge, skills, and behavior [35]. Group interactions play a major role in the development of teamwork skills. A promising web-based environment for the training of teamwork skills is a multiplayer serious game. Serious games can offer challenging and realistic scenarios that encourage learners to explore various situations and perform activities as a team, thus allowing mutual interaction [36]. Moreover, games can provide immediate feedback about the user's actions and guidance in learning, which is mainly important for novices [37]. Through serious

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games, learners can experience the consequences of their actions in a safe and controlled environment.

In summary, well-designed multiplayer serious games have the potential to enhance students' teamwork skills, especially in a blended training design, at a fraction of the cost of full-scale simulations. In a blended design, skills are pretrained in a web-based setting, allowing an activating, efficient, and flexible form of learning.

This Study

The interest in serious games has grown significantly over the past decades, especially in anesthesiology and obstetrics [38], and serious games are increasingly being implemented in health education for a variety of users [39]. Despite its potential, studies in the field of serious games targeting cognitive (clinical) skills are still sparse. A simulation game designed to teach residents (cognitive) acute care skills, as a preparation for face-to-face training, has been shown to be effective in improving these skills [40]. In addition, a web-based emergency room game for interprofessional education improved teamwork attitudes among medical and nursing students [41]. Moreover, Keith et al [42] found that playing video games as a team improved team performance, probably related to team cohesion processes. However, robust studies on game effectiveness and design choices are still inconclusive owing to the low quality of the evidence and paucity of studies included in meta-analyses [43-45].

Given the increasing relevance of blended training designs, it is important to gain insight into the potential of web-based learning environments for the development of teamwork skills.

We know that to learn a skill, tasks must be applied in an authentic context [37]; consequently, a game environment should stimulate the application of that specific skill. It is not yet clear which teamwork skills can be facilitated by serious games (as part of a blended training design). Therefore, this study examined the extent to which teamwork skills are used in the multiplayer game, *Team Up!* (more information about this game is provided in the *Materials* subsection of the *Methods* section). Findings can contribute to a better understanding of the potential of serious games for developing teamwork skills. In addition, they can inform designers and trainers in implementing an effective blended design, by helping to decide what skills require more attention in the face-to-face training sessions.

This study aimed to investigate the teamwork principles that were used in the game. As teamwork and communication between team members in the game occurred through individual and team chat, we qualitatively analyzed the game chat data. The type of teamwork principles used may relate to the level of teamwork experience of the players. Therefore, we performed *2 qualitative studies*. The first (main) study was conducted with fifth-year medical students (the primary target group of the game) and the second (conceptual replication) study was conducted with teamwork experts. The second study was conducted to increase the robustness and ecological validity of our findings. Teamwork experts were CRM trainers or physicians and residents in anesthesia department, both well trained in teamwork and use of CRM principles. We hypothesized that both groups of participants would apply the main teamwork principles during gameplay.

Methods

Ethics Approval

The study was approved by the Medical Ethics Review Committee for medical research using human participants from the relevant medical university (protocol ID BD1).

Recruitment and Data Collection

Study 1

The game, *Team Up!* was played during a mandatory session in the fifth year of the medical curriculum, as part of a course on *teamwork and prevention*, in Rotterdam, the Netherlands. This course consists of (1) an e-module on important teamwork principles; (2) the *Team Up*! game, where these principles can be applied with web-based patients; and (3) a (live) scenario training in a group of 12 students. The course is offered 5 times in an academic year to cohorts of approximately 60 to 90 medical students.

Before the start of the game session, all students received an email from their teacher with information about the course, study, and how to download the game on a mobile device. In the week before the study, participants were asked to read the e-module on teamwork principles at home. At the beginning of the study, students were asked to participate and (if so) to sign an informed consent form and provide permission to use their data for research purposes. All students who were invited (cohort 1: 60/144, 41.7% students and cohort 2: 84/144, 58.3% students) participated in the study (100% response), resulting in a final sample size of 144 students. Given that the study was conducted in a real educational setting, our sample size was limited to students from these cohorts.

We defined a priori that participants would be excluded when data were missing (eg, owing to technical problems) or if instructions were not adhered to. These exclusions were independent of the game scores. The main researcher was unfamiliar with the students and unaware of the group's characteristics. Participants were divided into groups of 4 by their teacher, resulting in 36 groups of participants. During the 90-minute session, participants played the game *Team Up!* on their mobile devices. The teacher indicated which scenario they should play, consistent with the current subject matter (students within a cohort played the same scenario). All conversations in the chats were stored, including data on the scenarios and team roles. In addition, game performance data (outcomes at the 3 points in the scenario) were collected, and the time spent on the game and the team chat was recorded. Owing to practical (COVID-19–related) reasons, the first cohort played the game at home and the second cohort played it in the classroom. As students in both settings were asked to play the game as a preparation for face-to-face training and used chat for communication, we did not expect or notice any differences in responses between these 2 settings.

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Study 2

Similar to study 1, potential participants from 2 medical centers received an email from their training coordinator, with information about the study and an invitation to participate. When they showed interest to participate, a suitable session was planned and participants received instructions on how to download the game. We were satisfied with a small group of participants compared with study 1, as this study was used as a conceptual replication study. In total, 24 health professionals (*experts*) were invited. All participants provided permission to use their data for research purposes and signed an informed consent form at the beginning of the study.

Of the 24 participants, 4 (17%) were CRM trainers from a Dutch Medical University Center and 20 (83%) were anesthesiology residents from 2 Dutch Medical University Centers. The CRM trainers participated in their free time, and the residents participated during one of their mandatory courses. Participants were divided into groups of 4 by the training coordinator, resulting in 6 groups of participants. The researcher was unfamiliar with the residents and unaware of the group's characteristics.

Owing to practical reasons, 4 groups played the game via the web, from home, or at their workplace. Hence, 2 groups played it in a classroom. During the 90-minute session, participants played the game on a mobile device. The main researcher and coordinator were present and indicated the scenario they should play. The nature of the study was explained to the participants later.

Materials

Preparatory e-Module on Teamwork Principles

In the week before the study, participants of study 1 were asked to read the e-module on teamwork principles to develop their knowledge in this field. This e-module was not mandatory and had no consequences for participants. The e-module covered the basic principles of CRM and teamwork tools and included interactive questions and patient cases to test and apply knowledge. CRM principles that were discussed include the main risks in interprofessional teamwork, situational awareness, stress management, and decision-making processes. Participants in study 2 did not have to read this e-module, as they were already familiar with these theoretical principles.

Multiplayer Serious Game Team Up!

Team Up! is designed and produced on behalf of the Erasmus University Medical Center, in collaboration with a game company, (&Ranj), to train students' teamwork skills. It is a multiplayer game, in which 4 players have to collaborate in different roles in realistic web-simulated emergency situations.

Figure 1 shows screenshots of the game *Team Up!* (in Dutch). The screenshots show the screen in which players select one of the patient cases (Figure 1A); the screen in which players select a role (student nurse, intern, nurse, or physician; Figure 1B); and the player dashboard, showing (top to bottom) the patient's condition, the remaining *team up* (group chat) time, and an overview of actions that can be performed by each role at that moment (Figure 1C).

The scenarios were developed and validated by an expert group, consisting of a clinical expert, a CRM expert, game designers, and an educational advisor. The game was designed by an experienced Dutch serious games design company and pilot-tested with the target group (medical students) before implementation. The primary aim of the game was to train students' interprofessional teamwork skills under time pressure, using clinical scenarios. The 2 scenarios that were played by participants from this study (described in Multimedia Appendix 1) were situated in an intramural care context (patient at the hospital) and in an extramural context (patient at home).

The game contains a tutorial scenario to familiarize players with the interface of the game: one-to-one chat, group chat, actions to choose from (eg, examine the patient, determine glucose, talk to the patient's daughter, and choose a diagnosis), overview of the patient's general condition, and patient's detailed file. At the beginning of the game, players select one of the 4 roles (physician, nurse, medical student, and student nurse) and can choose from several specific actions (matching their role) to provide the best possible care for a patient in a challenging and realistic medical scenario. To illustrate, in the extramural scenario, with a primary care sociomedical focus, players visit an older patient at home who has fallen and was unable to get up. They have to make a diagnosis (hypoglycemia resulting from an inadequate diet owing to forgetfulness) and provide solutions for the middle to long term (diabetes regulation, organizing meals on wheels, etc).

To collect relevant information and make correct decisions, players have to communicate effectively with each other using one-on-one and team chat functions. Individual players receive important information that they have to share in time. For instance, the student nurse talks to the daughter and hears about her forgetfulness in taking meals, and the resident receives information on the glucose level. If they fail to communicate this information effectively and make incorrect (or no) decisions, the patient's condition will deteriorate.

Each scenario should be solved within 30 minutes. During that time, the patient's condition is shown as improving or deteriorating (with a circle in green or red). The use of the group chat is limited in time to create time pressure. On their dashboard, players can see how much time is left for the group chat, how much time they have spent on the scenario so far, what actions they and other team members are performing, how much time this takes, the patient's condition, buttons to the patient's file, the team chat, and the one-on-one chats (refer to Figure 1). Each scenario consists of 3 parts. After each part, players receive brief feedback on their team's performance—whether they completed that part of the scenario successfully, how much time it took them, and how much time was left for the team chat. For simulation training, debriefing is known to improve performance in a clinical setting [46]. Therefore, debriefing was also implemented in the game.

At the end of each scenario, players are invited to reflect on their teamwork, guided by instructions such as the following: "Have a group chat conversation on the following statement: As a team, we have collaborated and communicated effectively and efficiently." This is followed by individual reflection, in

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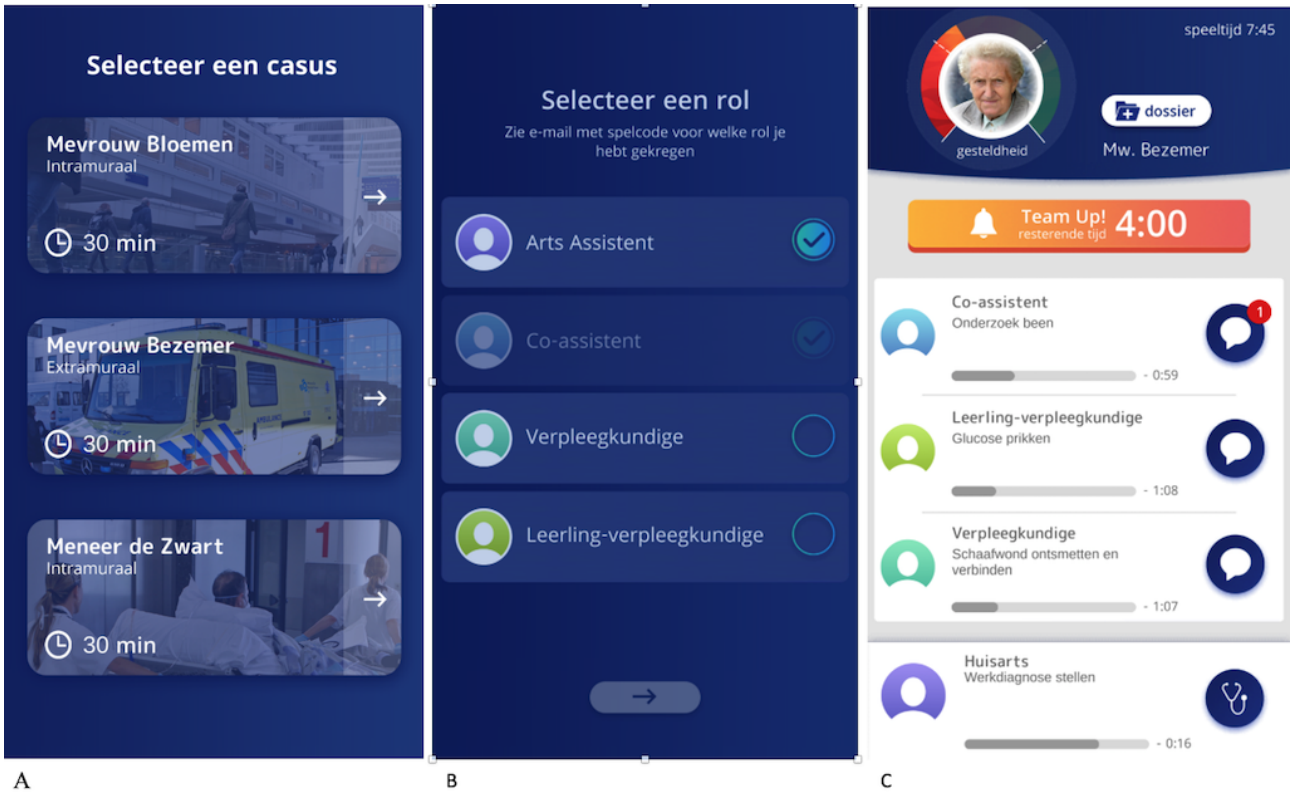
which participants have to reflect on their own contribution to teamwork, guided by the following instruction: “Reflect on your own role, based on the next questions: What went well? What could be improved or done differently?”

The serious game, *Team Up!* is currently implemented in the (medical) curriculum of participants of study 1 (ie, a Dutch Medical University Center). The game is used as web-based preparation for face-to-face scenario-based interprofessional teamwork training, followed by individual assessment of teamwork skills.

Figure 1. Screenshots of the game Team Up! (A) selection of patient cases, (B) selection of player's role, and (C) dashboard with the player's task progress.



Data Analysis

We conducted qualitative analyses, using a deductive approach, on the conversations in the chats. We started with concepts attributed to teamwork, more specifically CRM principles [19], and tested its implications in our chat data. For study 1 (among students), the first author (LP) and second author (TF) developed an initial coding scheme. Thereafter, they independently read and coded the conversations of 1 group in the first cohort line by line to capture concepts related to CRM. After a discussion between the raters about the discrepancies until consensus was reached, the initial coding scheme was refined to obtain a conceptual framework for chat conversation analyses (Multimedia Appendix 2). The remaining conversations of the groups in the first cohort were coded by LP. Next, LP and a research assistant (Roan Kasanmonadi) independently read and coded the conversations of 1 group in the second cohort. After the discrepancies were resolved by discussion, Roan Kasanmonadi coded the remaining conversations of the groups in the second cohort. Points for discussion were constantly discussed with LP and TF. The research team subsequently categorized the codes and identified the relationships between the CRM themes. During the final stage of analysis, the research team discussed the CRM themes and the extent to which the CRM principles were used in the game. To facilitate this process, LP constructed concept maps, presenting main themes, subthemes, and their relationships. LP, TF, and Roan Kasanmonadi captured reflections, ideas, and interpretations in memos throughout data analysis. Data analysis was supported by the qualitative data analysis and research software ATLAS.ti [47].

The qualitative analyses for study 2 (among experts) were conducted in a similar manner as in study 1. However, this time, the first author (LP) and a research assistant (Joost Jan Pannebakker) independently read and coded the conversations of 1 group line by line to capture concepts related to CRM. After a discussion about the discrepancies until consensus was reached, the remaining conversations of the groups were coded by Joost Jan Pannebakker. The research team subsequently discussed the CRM themes.

Results

Overview

The results of our analyses are described according to a conceptual framework of important teamwork principles in five main themes: (1) creating shared situational awareness, (2) decision-making, (3) communication, (4) team management aspects, and (5) team debriefing. Refer to Multimedia Appendix 2 for the coding scheme.

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We will describe the results of study 1 (among medical students) and study 2 (among experts) combined, as the findings may be group-related (students are novices in teamwork) and it seems interesting to compare the findings between groups with different experiences.

Shared Situational Awareness

In the team chats in study 1, we observed elements of trying to build and maintain shared situational awareness. Participants sometimes tried to create a comprehensive overview of the patient's situation by asking for missing information or by summarizing, using the team chat function. The created situation overview usually remained fairly general; requesting additional views or information was often lacking. Textbox 1 shows examples of aiming for shared situational awareness.

In study 2, similar to study 1, participants tried to create a comprehensive picture of the situation by asking for missing information or by summarizing. They often summarized efficiently (ie, point by point) and quickly returned to their own tasks. The created picture of the situation (again) usually remained fairly general; follow-up from the other team members was often lacking. Textbox 2 shows an example of the chat.

Textbox 1. Shared situational awareness—examples from 2 student groups.

Example 1

- "Sorry, did anyone ask about her eating pattern? Or her compliance to therapy? We need to know those two things. Yes, she finishes her plate ha-ha. Don't know about therapy compliance. She takes all of her medication. Okay, I know enough now." [Group 4; cohort 1]

Example 2

- "What information do we have right now? Glucose is 2,8. Fell down, she did not feel that coming, does not know whether she's been unconscious. Is feeling sweaty now. No further complaints. No chest pain, no heart palpitations. No loss of feeling in arms or legs. That's it, I believe. Great. No wounds? No. Intox? Do you know whether she fell on her head?" [Group 23; cohort 2]

Textbox 2. Shared situational awareness—example from an expert group.

Example

- "We think UTI [urinary tract infection] with SIRS [systematic inflammatory response syndrome] and Hypoglycemia right? Yes agree. Yes she's confused, but no further neurological abnormalities." [Group 5]

Decision-making

In study 1, among students, we observed decision-making aspects such as re-evaluating decisions or situations and anticipating and planning (Textbox 3 shows a few examples).

In almost all groups, participants regularly set priorities and focused on issues that needed attention first. Usually, this happened when a team member identified that the patient's condition was deteriorating. Participants either indicated that something needed more attention or asked their team members what should be done first. In most cases, this was followed up by the team members; they subsequently shared and requested information or shared their own thoughts. This is consistent with the objective of allocating attention wisely, that is, looking at the overall picture of the situation at set times. Remarkably, a justification for why something should be prioritized was often lacking. Therefore, the team members were less involved in a joint thinking process and were rarely asked about their motives.

In study 2, among experts, we observed a wide range of decision-making processes: re-evaluating the patient's progress, noticing changes in the patient's condition, and subsequently, making judgments about continued care or treatment adjustments (refer to Textbox 4 for examples). Re-evaluations of decisions or judgments seemed to be more present in the experts' chats compared with students' chats. Similar to participants of study 1, they did not use explicit prevention of fixation errors.

In almost all expert groups, players—again—regularly set priorities and focused on issues that need attention first. Usually, they either indicated that something needed more attention or asked their team members what should be done first. In most cases, this was followed up by the team members; they subsequently shared and requested information or shared their thoughts. Compared with students, experts more often seemed to justify why something should be prioritized.

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Textbox 3. Decision-making—examples from 3 student groups.

Example 1

- "We have to check whether she has a fall spot on her eye or head." [Group 16; cohort 2]

Example 2

- "What room are we going to? Wat type of patient is coming? Do we all need to go to one room? We all need to go to the same room. This can be done in a normal room. I think acute. Can possibly deteriorate right? I would choose acute. Acute room? Okay." [Group 19; cohort 1]

Example 3

- "First correct her Hypoglycemia, then stabilize, then examine leg." [Group 21; cohort 2]

Textbox 4. Decision-making (re-evaluation)—examples from 2 expert groups.

Example 1

- "Still sounds as a hypo.. delirium.." [Group 7]

Example 2

- "Continue with the present plan?" [Group 7]

Communication

In study 1, our analyses showed that general communication techniques, such as sharing and requesting information, were frequently used. More specific communication techniques such as confirming a request (*closed loop*) and inviting other team members to add ideas or thoughts (*speak up*) were also observed, both in the team chat and one-on-one chats (Textbox 5).

Regarding *closed loop communication*, the recipient usually confirmed the request (refer to examples in Textbox 5), but the confirmation by the requester that this message has arrived was usually lacking (although this is not strictly necessary in closed loops). In addition, the completion of a task was not always confirmed to the requester in the chats. This may be caused by the game layout, in which the completed task remained visible.

Regarding *speak up*, results showed that participants used it quite often. Inquiries were regularly initiated. Furthermore, thoughts and hypotheses were shared and subsequently discussed; however, they were quite brief discussions with few open questions.

Taking a time-out was not often explicitly mentioned in the chats. Time-outs were mainly used to bring focus and coordinate with each other. Starting the team chat in the game may also be considered as taking a time-out. Participants were informed before playing the game that they could use the team chat to coordinate with each other or to check whether they all agree. The team chat was mainly used to share and request information among all team members.

In study 2, among experts, general communication techniques such as sharing and requesting information were also often used. Participants communicated very succinctly and efficiently, which is probably the result of their experience in the clinical workplace. Compared with students, they communicated relatively more according to the *closed loop* principle—repeating that a requested task will be performed. Textbox 6 shows a few examples.

Requests were usually repeated by the recipient, but the requester seldom acknowledged that this message had arrived. Moreover, the completion of a request was generally not confirmed to the requester.

Speak up was used relatively more often by participants in study 2 (experts) compared with participants in study 1 (medical students). When one of the team members discovered a discrepancy or vital new information or when they had doubts about something, they often shared it with the other team members and acted upon it. Although thoughts and hypotheses were again often shared, the expert participants more often used open-ended questions to collect additional information from the other team members.

Explicitly taking a time-out to bring focus and to coordinate with each other was only observed once in the chat data. However, as stated previously, one could argue that starting the team chat implies taking a time-out. Participants used the team chat effectively by regularly summarizing the available information, discussing the status quo, and ensuring agreement. Usually, 1 team member summarized, whereas ideally, they would also complement each other.

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Textbox 5. Communication (closed loop and speak up)—examples from 3 student groups.

Example 1

- "Could you inform the daughter? Yes I will." [Group 4; cohort 1]

Example 2

- "Can you do the urine test? Yes, I'll do the urine test." [Group 8; cohort 2]

Example 3

- "Everyone in agreement? Yes. Yes. Yes." [Group 13; cohort 2]

Textbox 6. Communication (closed loop and speak up)—examples from 3 expert groups.

Example 1

- "Shall I give her a coke?

Yes give her a coke.

I'll give a glass of coke to the patient." [Group 3]

Example 2

- "What are we thinking of?" [Group 4]

Example 3

- "I have the feeling we are missing something" [Group 7]

Team Management

We observed some team management principles in study 1, such as appointing leaders and followers, distributing the workload, and calling for help. Not all teams appointed leaders. Cognitive aids were rarely used. The division of team roles and workload was sometimes discussed at the beginning of the gameplay. When it was decided or mentioned who would take the lead, the leader immediately assumed that role. They distributed the workload among team members—which was rarely observed in groups without a clear leader—and checked whether all team members agreed to a major decision. In these groups, teamwork improved; the team chat was used functionally, and team members communicated effectively, for instance, by using closed-loop communication. The division of roles was discussed more often during the group debriefing (refer to the following paragraph), that is, *after* the scenario had been completed.

In contrast to our findings in study 1, the division of roles—including designating leaders and followers was frequently observed in the chat data of study 2. When participants assigned a leader, that leader frequently distributed the workload among team members, took the initiative in determining which working method is to be followed, and assumed responsibility for overseeing the situation (refer to Multimedia Appendix 3 for examples). Again, management principles, such as calling for help and using cognitive aids, were rarely observed in this group. Examples of team management principles of both groups are presented in Multimedia Appendix 3. Designating leaders and followers appears to be related to effective communication between team members, as teamwork principles were better applied in groups in which roles were clearly divided. Again, the division of roles was discussed more often during the group debriefing, *after* the scenario had been completed.

Team Debriefing

Analyses of the debriefing chats in study 1 (students) revealed that participants were usually able to reflect on their teamwork and identify the causes of both good and poor teamwork. This sometimes led to agreements regarding better division of roles in the next scenario (refer to Multimedia Appendix 3 for an example). In addition, some groups also discussed their communication and how to improve this in the subsequent scenario. However, in general, the groups only identified what went well and what went wrong in their communication and did not explicitly discuss the follow-up steps.

Results from study 2 (experts) showed that participants were usually able to identify the causes of both good and poor teamwork during the team debriefing (refer to Multimedia Appendix 3 for examples). However, this rarely led to concrete agreements for the next scenario. Discussions about communication were also limited; that is, they mainly briefly identified what went well and what went wrong in terms of communication and did not explicitly discuss the follow-up steps.

Sometimes, team members took the initiative to start a discussion with the entire team about their teamwork and communication, but there was rarely any response. Examples of debriefing by both groups are presented in Multimedia Appendix 3).

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Summary of Results

In summary, our findings showed that both students and experts used important teamwork principles during gameplay, such as creating shared situational awareness, decision-making, general and specific communication strategies (eg, closed loops and speak up), team management actions (dividing tasks), and debriefing reflections. Experts also used some principles that students rarely used (eg, appointing leaders and dividing tasks). Experts used more open communication strategies (eg, speak up), performed more re-evaluation, and provided better justification of decisions. Prevention of fixation errors and use of cognitive aids were less observed among both groups, and debriefing conversations in both groups remained relatively superficial.

Discussion

Principal Findings

In this study, we examined the teamwork principles that were applied in a multiplayer serious game by medical students and teamwork experts. We found that both undergraduate students and experts practiced important teamwork principles during gameplay, such as shared situational awareness, decision-making (re-evaluation and prioritizing), communication (closed loop and speak up), and team management (appointing a leader and distributing the workload). Among experts, we observed the use of similar teamwork principles often on a moderately high level.

The teamwork game was designed to allow medical students to practice teamwork principles during medical emergencies. Findings can contribute to a better understanding of the potential of multiplayer serious games for developing these skills and can inform designers of blended teamwork training. We conducted qualitative analyses, using a deductive approach, on the conversations in the chats. We started with a conceptual framework of important teamwork themes (a CRM framework [19]): creating shared situational awareness, decision-making, communication, team management, and debriefing. We conducted 2 qualitative studies: a main study among medical students and, as a conceptual replication study, a study among teamwork experts (experienced residents and trainers in teamwork).

Our results showed that both students and teamwork experts applied most teamwork principles (ie, the CRM principles) during gameplay. Among students, we observed the creation of shared situational awareness, decision-making, important communication, and team management principles (closed loop and distributing the workload). Some teamwork principles were less or rarely used, such as requesting additional views when creating shared situational awareness, preventing fixation errors, appointing leaders, and applying speak up with open questions. Debriefing was usually conducted superficially—a brief exchange of good and poor teamwork elements, without a thorough discussion about the team members' contributions and how it may be improved in the next scenario. In general, the more complex elements of teamwork were less observed in the web-based game played by the students. Among experts, we also observed the use of all main teamwork principles. However, they used more re-evaluation, closed-loop communication, and open questions with speak up, and they appointed leaders and divided roles more often than the students. In general, compared with the students, the experts' communication was more efficient and succinct, and they substantiated the assumptions more often, matching their expertise level.

The fact that most teamwork principles were applied in this multiplayer game indicates that games can provide a flexible and activating learning environment in which teamwork principles can be exercised safely on a basic level. Considering the importance and complexity of these skills and the fact that face-to-face training is cost intensive, this is a promising finding for educational practice. Students can use these scenarios as often as they want, in different roles, and with different peers. Once developed, this type of game can be frequently used for training, without extra costs. Moreover, for students, this type of game provides the opportunity to apply and *experience* teamwork principles in a realistic context, which is much more meaningful and effective than reading about these principles [48].

In the current (*Team Up*!) game design, the appearance of specific role-related tasks and information, in combination with the one-to-one and team chats, created the necessity and opportunity to collaborate. The web-based patient, deteriorating or improving during gameplay, probably created a sense of urgency and feedback. Previous study has shown a consistent association of technology-enhanced simulation training in health professions education with positive effects on knowledge, skills, and behaviors [35]. However, this is not yet established for serious games specifically and, therefore, more validation of this format is needed [44]. Furthermore, more studies on the effectiveness of specific design choices in games are needed [49], to know what characteristics facilitate the use of communication and teamwork.

The observation that teamwork experts applied some principles on a more elaborate level (eg, more open questions and more closed-loop communication) may indicate that the use of these principles is related to expertise. The game scenarios facilitated the use of these principles for teamwork experts on a higher level than for novices. Hence, the game appears to be a promising learning environment for training these skills for groups with different experiences. Games have been shown to aid the development of complex skills in individual medical practitioners [40]. In this study, we demonstrated that a multiplayer game could elicit the application of teamwork principles both in novices and experts. As the application of these principles is essential to learn the skills, we view this study as a vital first step in investigating the potential of multiplayer game–based learning for teamwork skills. It would be interesting to investigate what support novices need to apply these skills on a more elaborate level through further studies. Examples of potentially helpful support are checklists (eg, with CRM principles) in the game. Checklists can act as task support that helps students adhere to certain principles or procedures [37].

For simulation training, debriefing is known to improve future performance in a clinical setting [46], and therefore, it is a

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crucial part of the training. In this study, we observed that debriefing as a group (after performing the web-based scenarios) was conducted superficially by both students and experts. The general questions that were provided during debriefing in the game led to a superficial discussion on teamwork and roles. Given the relatively unguided format, it may not be surprising that most player groups did not engage in deep reflection. In general, reflecting in depth as a group is difficult without instructor-led guidance or a more structured format; however, some groups managed to reach a deep analysis level. According to the Promoting Excellence and Reflective Learning in Simulation model of debriefing, including reaction, description, analysis, and application [50], most participants were in the reaction phase. This raises the question of how the transition to the description or analysis phases can be stimulated. Using instructor-led guidance is not a solution in a game context, as this would severely limit the possibilities of flexible learning and entail high costs. Different studies have showed that structured self-debriefing can be equally effective as instructor-led debriefing [51,52]. Furthermore, Van der Meij et al [53] suggested describing specific and observable actions and criteria for good teamwork in the debriefing format. Further studies could clarify the effectiveness of this type of debriefing formats in improving the quality of reflections and team debriefing.

Some specific teamwork principles were not applied by both player groups, such as using cognitive aids and preventing fixation errors. This is likely to be related to the scenarios (these teamwork principles may not be needed for solving specific patient scenarios) or the context of the game (owing to functionality or interface). Some game functions appeared to limit the possibilities to use specific teamwork principles. To illustrate, it is probably not logical to apply closed-loop communication when the messages remain in the chat and when the tasks that team members have performed remain visible in the game app (as opposed to verbal instructions in the real-life environment). In face-to-face training, these less-used principles can be given extra attention. We also noticed that some principles, such as planning and decision-making (eg, while preparing for the hospitalization of a patient), were observed more often in some scenarios than in others. This implies that offering a variety of game scenarios, aligned with specific teamwork learning goals, is important. In addition, some more complex teamwork principles can probably best be trained in a face-to-face simulation setting. Then, the multiplayer game can serve as an (efficient) preparation for skills training in a blended design.

Strengths and Limitations

In this study, we investigated whether a multiplayer serious game, used in a medical curriculum for fifth-year medical students in the Netherlands, facilitates the use of important teamwork principles. We were able to confirm that all main principles were applied in the web-based patient scenarios. As described previously, these results have important educational value for training students in teamwork skills.

A limitation of this study is that we did not investigate whether the gameplay actually improved participants' teamwork skills or whether transfer of teamwork skills to a setting outside the game occurred. Instead, we deliberately chose to investigate the teamwork principles that were used during gameplay because the game was implemented in the skills training in our curriculum and we did not want to deny students access to the game (as would be necessary for a randomized design with a control group). This would be an interesting object for future studies, for example, comparing a group that used the teamwork game with a group that watched a video on teamwork principles, followed by scenario assessments.

Another limitation is the difference in recruitment between the groups of participants of study 1 (students) and study 2 (experts). Regarding students, the whole semester group played the game (as part of their curriculum) and was approached for the study. Regarding experts, specific groups of experts were asked to play the game and participate in the study (outside the context of a course). We believe that this was inevitable because the game was part of the medical curriculum and acceptable because the expert data were merely used as an additional benchmark. Although this made a direct comparison between the 2 groups more difficult, we did not see indications of biased results.

Conclusions

In this study, we examined the teamwork principles that were applied in a multiplayer serious game by medical students and teamwork experts. We found that the game facilitates the application of important teamwork principles among medical students, and they were related to all main teamwork themes: shared situational awareness, decision-making (re-evaluating and prioritizing), communication (closed loop and speak up), and team management (appointing a leader and distributing the workload). Among teamwork experts, we observed the use of similar teamwork principles often on a higher level: more justification of decisions, re-evaluation, closed loops, and open questions.

A multiplayer game to train teamwork skills appears to be a promising learning environment, as it can be used as a flexible training tool to safely practice teamwork principles and prepare for face-to-face training. Hence, during face-to-face training, students can focus more on exercising complex teamwork principles and processing feedback.

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Conflicts of Interest

None declared.

Multimedia Appendix 1
Description of scenarios 1 and 2.
[DOCX File , 14 KB - games_v10i4e38009_app1.docx]

Multimedia Appendix 2
Coding scheme for the teamwork principles.
[DOCX File , 17 KB - games_v10i4e38009_app2.docx]

Multimedia Appendix 3
Textboxes with examples from chats on team management and debriefing.
[DOCX File , 16 KB - games_v10i4e38009_app3.docx]

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Abbreviations

CRM: Crew Resource Management

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Original Paper

Effects of Cybersickness Caused by Head-Mounted Display–Based Virtual Reality on Physiological Responses: Cross-sectional Study

Yoon Sang Kim[1], PhD; JuHye Won[2], MS; Seong-Wook Jang[3], PhD; Junho Ko[4], PhD

[1]BioComputing Lab, Institute for Bio-engineering Application Technology, Department of Computer Science and Engineering, Korea University of Technology and Education, Cheonan-si, Republic of Korea

[2]BioComputing Lab, Department of Computer Science and Engineering, Korea University of Technology and Education, Cheonan-si, Republic of Korea

[3]Assistive Technology Research Team for Independent Living, National Rehabilitation Institute, Seoul, Republic of Korea

[4]AirPlug Ltd, Seoul, Republic of Korea

Corresponding Author:
Yoon Sang Kim, PhD
BioComputing Lab, Institute for Bio-engineering Application Technology
Department of Computer Science and Engineering
Korea University of Technology and Education
1600, Chungjeol-ro, Byeongcheon-myeon, Dongnam-gu
Cheonan-si, 31253
Republic of Korea
Phone: 82 0415601496
Email: yoonsang@koreatech.ac.kr

Abstract

Background: Although more people are experiencing cybersickness due to the popularization of virtual reality (VR), no official standard for the cause and reduction of cybersickness exists to date. One of the main reasons is that an objective method to assess cybersickness has not been established. To resolve this, research on evaluating cybersickness with physiological responses that can be measured in real time is required. Since research on deriving physiological responses that can assess cybersickness is at an early stage, further studies examining various physiological responses are needed.

Objective: This study analyzed the effects of cybersickness caused by head-mounted display–based VR on physiological responses.

Methods: We developed content that provided users with a first-person view of an aircraft that moved (with translation and combined rotation) over a city via a predetermined trajectory. In the experiment, cybersickness and the physiological responses of participants were measured. Cybersickness was assessed by the Simulator Sickness Questionnaire (SSQ). The measured physiological responses were heart rate, blood pressure, body temperature, and cortisol level.

Results: Our measurement confirmed that all SSQ scores increased significantly (all Ps<.05) when participants experienced cybersickness. Heart rate and cortisol level increased significantly (P=.01 and P=.001, respectively). Body temperature also increased, but there was no statistically significant difference (P=.02). Systolic blood pressure and diastolic blood pressure decreased significantly (P=.001).

Conclusions: Based on the results of our analysis, the following conclusions were drawn: (1) cybersickness causes significant disorientation, and research on this topic should focus on factors that affect disorientation; and (2) the physiological responses that are suitable for measuring cybersickness are heart rate and cortisol level.

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KEYWORDS

cybersickness; physiological responses; virtual reality; VR; head-mounted displays; heart rate; cortisol

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Introduction

The recent development of technologies such as head-mounted displays (HMDs) and motion-tracking devices has enabled active research on virtual reality (VR). VR is used in various fields, such as in games, education, medicine, and health care [1]. Although VR can improve the user's concentration by providing an immersive experience, some users may experience cybersickness, which is a type of motion sickness [2].

The most well-known theory for explaining motion sickness is the sensory conflict theory. According to the sensory conflict theory, motion sickness is caused by a discordance between the vestibular sense and the visual perception of body movement [3-6]. In addition, according to the sensory conflict theory, motion sickness is classified into motion-induced motion sickness (MIMS) and visually induced motion sickness (VIMS). MIMS is further classified according to the external environment as car, ship, and air (flight) sickness [7-10], and VIMS is further classified into simulator motion sickness and cyber motion sickness according to the display device [11,12]. Simulator motion sickness is caused in virtual training such as flying and driving [13-15], and cyber motion sickness is caused in virtual environments that are completely different from real ones [16].

Although more people are experiencing cybersickness due to the popularization of VR, no official standard for the cause and reduction of cybersickness exists to date. One of the main reasons is that an objective method to assess cybersickness has not been established. Vomiting has been used as a diagnostic criterion for motion sickness because it is difficult to assess other symptoms quantitatively [17]. However, because there are instances of motion sickness that do not accompany vomiting, the Motion Sickness Assessment Questionnaire (MSAQ) [18] and the Simulator Sickness Questionnaire (SSQ) [19] have been proposed to assess motion sickness symptoms. The MSAQ has been used extensively in traditional motion sickness studies; however, it is not suitable for VIMS assessment. The SSQ, which is optimized from the MSAQ and focuses on VIMS, is mostly used in studies assessing simulator sickness and cybersickness. Even though the SSQ is low-cost and easy to use, its objectiveness is questionable and its real-time implementation is difficult [20,21].

To solve this problem, research on evaluating cybersickness with physiological responses that can be measured in real time is required [22,23]. To assess cybersickness in terms of physiological responses, it is necessary to find out the factors that are correlated with cybersickness. Conventional studies have reported that physiological responses, such as specific frequency power bands of the electroencephalogram [24-26], gastrointestinal activity [27], heart rate [28-30], and skin conductance [31], can be used to assess cybersickness. In particular, heart rate has been reported to be related to the stress task when playing a video [29,30]. Although conventional research into cybersickness is extensive, this issue remains in the HMD-based VR context [32]. Many validation experiments are necessary to generalize these physiological responses. Since research on deriving physiological responses that can assess cybersickness is at an early stage, further research on various physiological responses is still required. Therefore, this paper deals with the effects of cybersickness caused by HMD-based VR on physiological responses.

Methods

Design and Setting

We performed an experiment where participants watched HMD-based VR content in the environment shown in Figure 1.

Conventional studies on the effect of the content itself have shown that rotational movement causes higher motion sickness than a linear one [33] and that a combined rotation of more than 1 axis causes greater motion sickness than a rotation of a single axis [34,35]. Based on those conventional studies, our HMD-based VR content was developed to intentionally cause cybersickness using Unity 3D (Unity Technologies) [36]. In addition, the longer the exposure time, the higher the level of cybersickness, so the playing time of the developed content was configured to be the least amount of time needed to measure the physiological response.

The developed content provided the user with a first-person view of an aircraft that moved (with translation and combined rotation) over a city via a predetermined trajectory.

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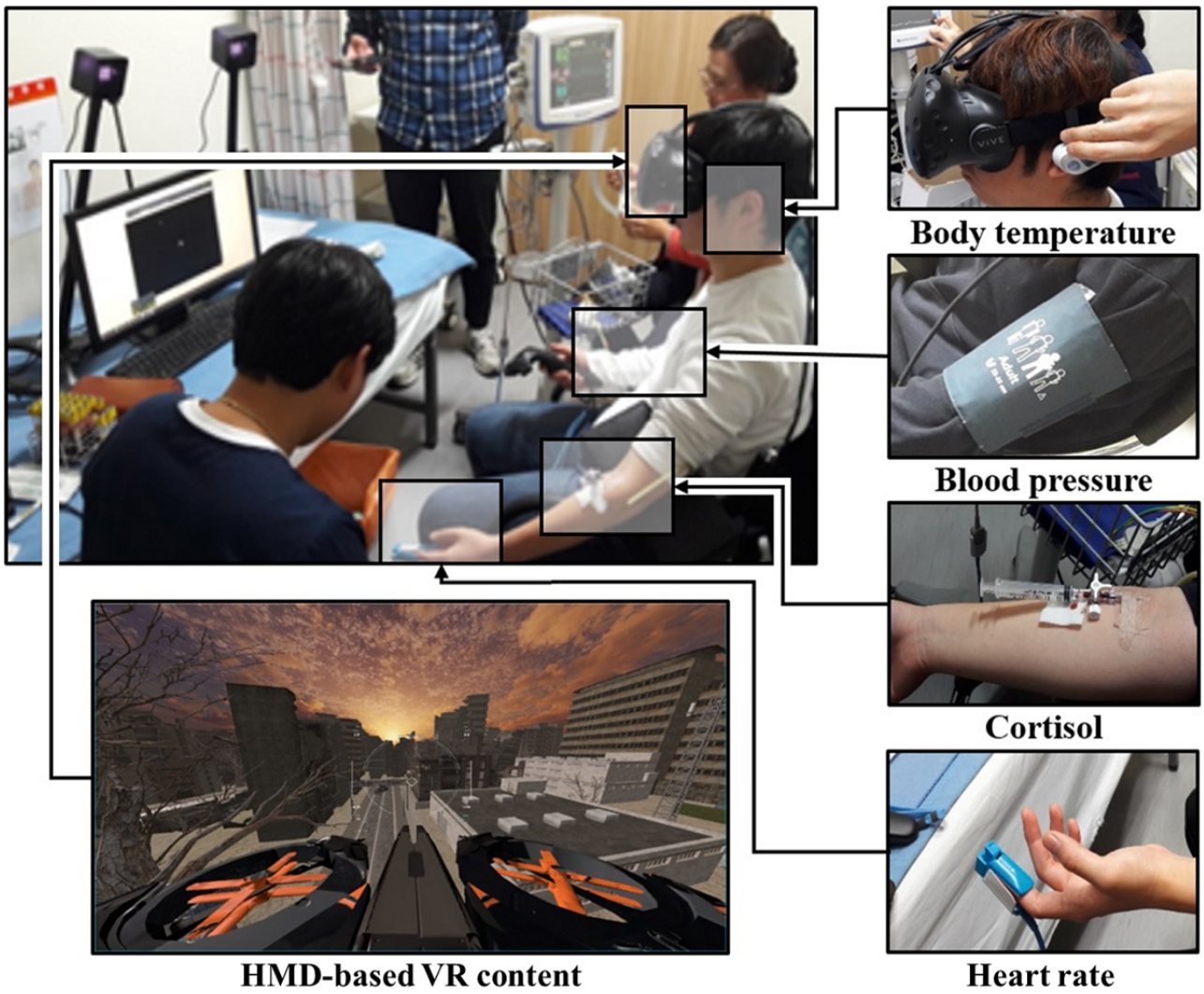
Figure 1. The experimental environment. HMD: head-mounted display; VR: virtual reality.



Questionnaire, Variables, and Equipment

The SSQ [19] was used to assess cybersickness. This questionnaire consists of 16 questions with 3 subscales corresponding to symptom clusters (nausea, oculomotor symptoms, and disorientation). Each question is measured on a 4-point scale from 0 to 3 points. A total score represents the complete symptom level of motion sickness. A higher score indicates more severe motion sickness.

In an experiment conducted on a Korean population [37], it was confirmed that the SSQ significantly increased in HMD-based environments compared to screen-based environments, which suggests it could have validity and reliability in measuring cybersickness.

The occurrence of motion sickness is highly related to the autonomic nervous system [38]. Therefore, in this experiment, physiological responses related to the autonomic nervous system were measured to examine whether or not the responses related to motion sickness can be applied to HMD-based cybersickness. We measured the following physiological responses that relate to the autonomic nervous system: heart rate, blood pressure, body temperature, and cortisol level. Blood pressure was measured as 2 values: systolic and diastolic. Systolic blood pressure indicates the highest pressure in the artery when the heart is contracted, and diastolic blood pressure indicates the lowest pressure in the artery right before the heart contracts again. Body temperature was measured with a digital thermometer. Cortisol, which is produced under stress, was measured from 4 cc of blood collected over 2 minutes with the support of a clinician at Cheonan Medical Center [39].

The HMD used in the experiment was the HTC Vive (HTC Corporation) [40]. To minimize the effect of the vestibular sense, we controlled body motion in addition to head translation and rotation.

Participants

A total of 16 undergraduate and graduate students (male: n=8, 50%; female: n=8, 50%) participated in the experiment. The participants had no history of problems associated with the nervous system, autonomic nervous system, and visual system. In addition, more than 8 hours of sleep was recommended to prevent increased cybersickness sensitivity among participants [41]. Prior to participation, we explained the experiment, apart from the objective, and then obtained written consent to participate.

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Procedures

The experimental procedure consisted of 3 steps (pre-experiment, experiment, and postexperiment) as shown in Textbox 1. In the pre-experiment step, SSQ and the physiological responses of the participants were measured.

In the experiment step, participants viewed the HMD-based VR content that we developed during the design phase. The participants sat and watched the VR content without moving. By making the participants concentrate only on watching the VR content, we ensured their stress level was affected solely by cybersickness.

In the postexperiment step, participants' physiological responses and SSQ outcomes were measured. Each step was performed for 2 minutes, and the total experiment time was 10 minutes.

Textbox 1. The experimental procedure.

Pre-experiment step

- Simulator Sickness Questionnaire (SSQ) measurement (2 minutes)
- Physiological response measurement (2 minutes)

Experiment

- Head-mounted display–based virtual reality content viewing (2 minutes)

Postexperiment step

- Physiological response measurement (2 minutes)
- SSQ measurement (2 minutes)

Data Analysis

We analyzed the data measured in the experiment using SPSS Statistics (version 21; IBM Corp) [42]. The data measured in the experiment were SSQ items, heart rate, body temperature, blood pressure, and cortisol. A statistical analysis (paired *t* test) was applied to find significant differences between the measured data in the pre- and postexperiment steps. SSQ scores from before and after the experiment were compared to detect the presence of cybersickness. If found, we analyzed how each physiological response was related to cybersickness in the HMD-based environment.

Ethics Approval

The study was approved by the institutional review board of the Korea University of Technology and Education (IRB-17122602).

Results

SSQ Analysis

The SSQ scores measured before and after the experiment are shown in Figure 2. In the pre-experiment step, the mean SSQ scores for nausea, oculomotor, disorientation, and total score were 4.17, 15.63, 5.22, and 10.75, respectively. In the postexperiment step, they were 32.79, 38.77, 64.38, and 49.32, respectively. From the measurement results, it was confirmed that all SSQ scores increased significantly, as shown in Table 1 (all *P*s<.05). This indicates that cybersickness was experienced by participants viewing the HMD-based VR content.

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Figure 2. The SSQ scores measured in the pre- and postexperiment steps. SSQ: Simulator Sickness Questionnaire.

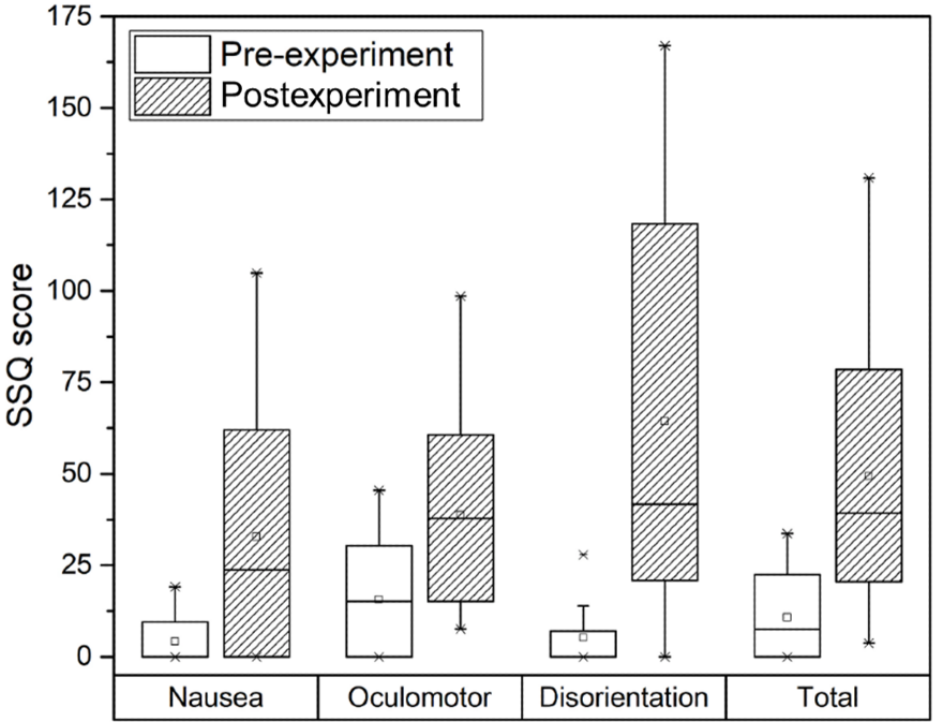

Table 1. The Simulator Sickness Questionnaire scores measured before and after the experiment.

Physiological response	Pre-experiment score, mean (SD)	Postexperiment score, mean (SD)	*t* (*df*)	*P* value
Nausea	4.17 (6.94)	32.79 (34.30)	–3.48 (15)	.003[a]
Oculomotor	15.63 (16.01)	38.77 (24.97)	–3.37 (15)	.004[a]
Disorientation	5.22 (10.01)	64.38 (58.15)	–3.93 (15)	.001[a]
Total	10.75 (11.74)	49.32 (38.00)	–3.89 (15)	.001[a]

[a]Significant *P* values.

Physiological Responses Analysis

The physiological responses measured in the pre- and postexperiment steps are shown in Table 2. Mean heart rate before and after the experiment was 78.06 bpm and 83.50 bpm, respectively. Our measurements confirmed that heart rate increased significantly (*P*=.01; Figure 3). This means that heart rate increased when cybersickness was experienced by participants viewing the HMD-based VR content.

Table 2. Physiological responses measured before and after the experiment.

Physiological response	Pre-experiment score, mean (SD)	Postexperiment score, mean (SD)	*t* (*df*)	*P* value
Heart rate (bpm)	78.06 (7.71)	83.50 (10.41)	–2.92 (15)	.01[a]
Cortisol (ug/dl)	7.75 (2.62)	10.59 (4.12)	–4.72 (15)	.001[a]
Body temperature (°C)	37.10 (0.28)	37.14 (0.21)	–1.33 (15)	.20
Blood pressure (mmHg)				
Systolic	130.81 (18.84)	117.31 (15.78)	5.43 (15)	.001[a]
Diastolic	76.69 (9.30)	67.50 (11.90)	4.43 (15)	.001[a]

[a]Significant *P* values.

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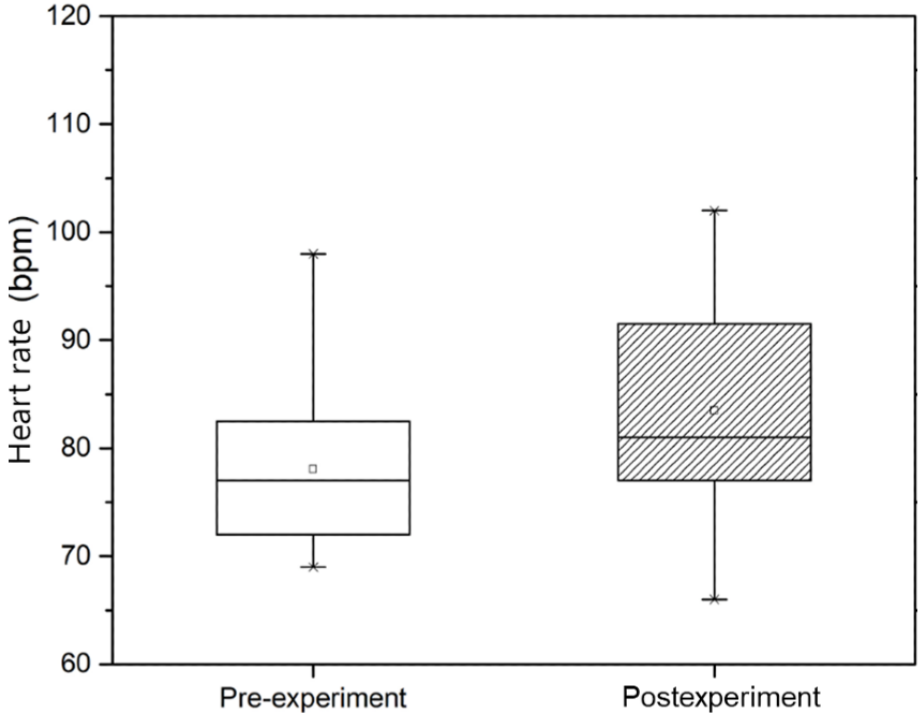
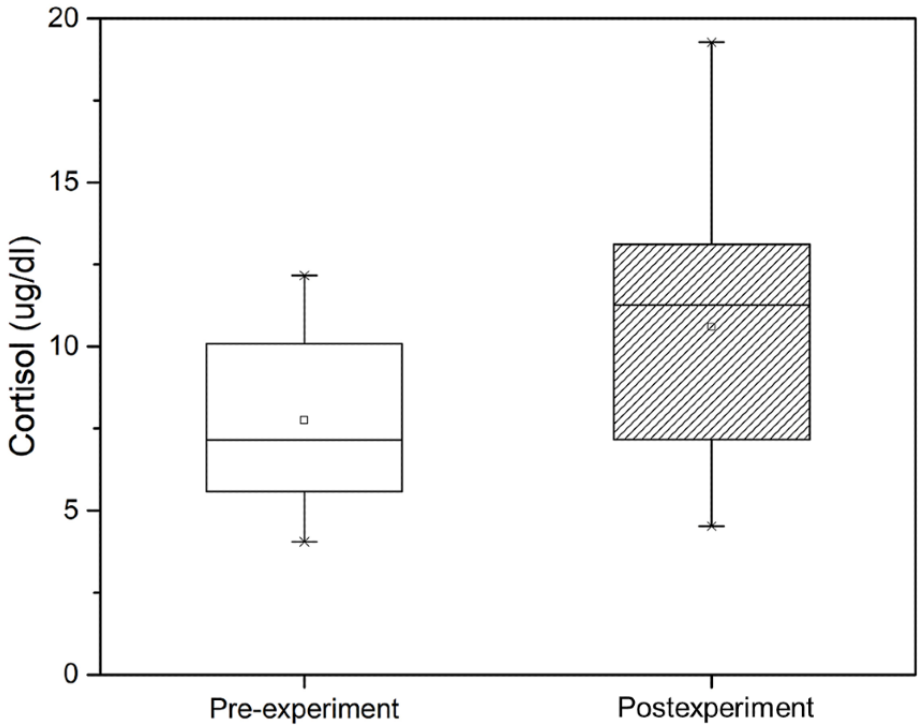
Figure 3. Heart rate measured in the pre- and postexperiment steps.



The mean cortisol level before and after the experiment was 7.75 ug/dl and 10.59 ug/dl, respectively. Our measurements confirmed that the cortisol level increased significantly (*P*=.001; Figure 4). This implies that the cortisol level increased when participants felt cybersickness.

Figure 4. Cortisol level measured in the pre- and postexperiment steps.



Mean body temperature before and after the experiment was 37.10 °C and 37.14 °C, respectively. As per the measurement results, body temperature increased (Figure 5), but there was no statistically significant difference (*P*=.20).

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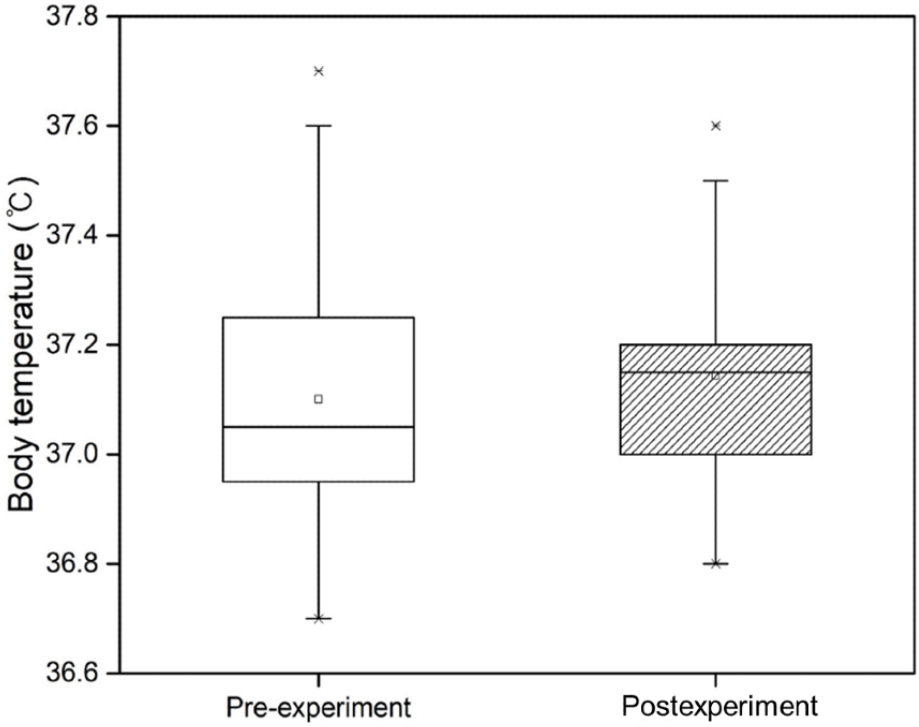
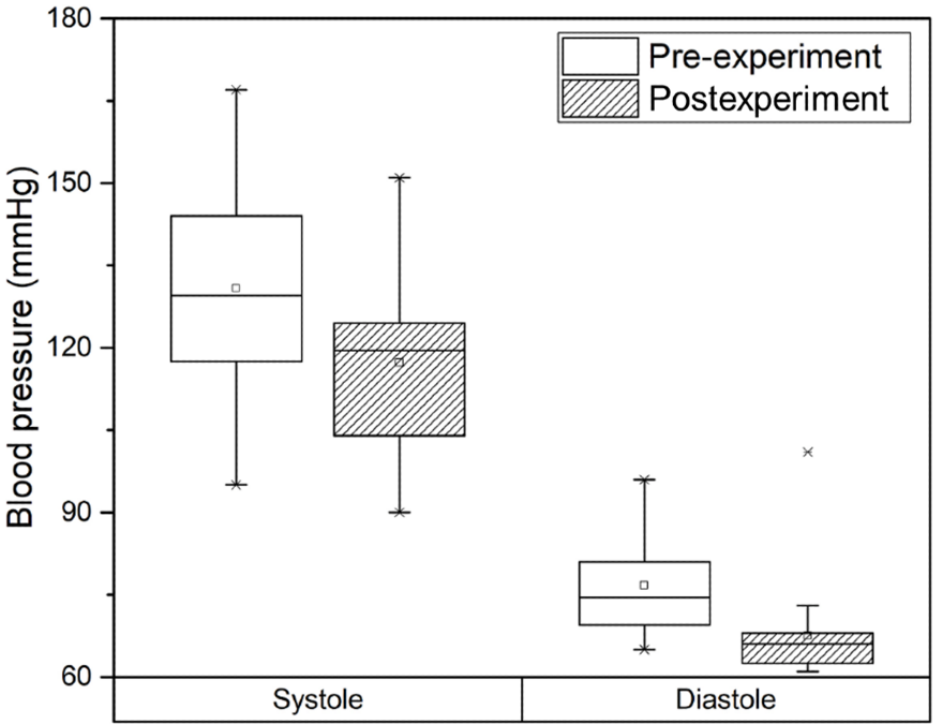
Figure 5. Body temperature measured in the pre- and postexperiment steps.



Mean systolic blood pressure before and after the experiment was 130.81 mmHg and 117.31 mmHg, respectively, whereas mean diastolic blood pressure was 76.69 mmHg and 67.50 mmHg, respectively. As per the measurement results, systolic blood pressure and diastolic blood pressure decreased significantly (*P*=.001; Figure 6). This means that blood pressure decreased when cybersickness was experienced by participants.

Figure 6. Blood pressure measured in the pre- and postexperiment steps.



Discussion

Principal Findings

This paper examined the effects of cybersickness on physiological responses when people watch HMD-based VR content. To this end, we performed statistical analyses of SSQ scores and physiological responses (using questionnaire responses and measurements, respectively) before and after the experiment.

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SSQ scores analysis in the pre- and postexperiment steps was performed to assess whether HMD-based VR content caused cybersickness. According to previous studies assessing various motion sicknesses [21], MIMS (car, ship, and airplane), simulator sickness, and cybersickness showed the highest increase in nausea, oculomotor, and disorientation, respectively. In this study, we found the highest increase in disorientation in cases of cybersickness. This result matches that of other studies (see Table 1 and Figure 2). This indicates that when there is no vestibular stimulation caused by the movement of the body and cybersickness is caused by visual stimulation through the HMD, significant disorientation occurs. This means that there is a secondary risk of walking accidents due to disorientation as well as a primary risk of cybersickness when watching HMD-based VR content. Therefore, we believe that studies on reducing cybersickness should focus on disorientation.

Physiological responses analysis in the pre- and postexperiment steps was performed to assess physiological response due to cybersickness. Significant effects on heart rate, blood pressure, and cortisol level were found in participants experiencing cybersickness (Table 2). Heart rate and cortisol level are closely related to stress. Heart rate is explained separately by the heart-body linkage hypothesis and the heart-body dissociation hypothesis [43]. The heart-body connection hypothesis states that when a person exercises, their metabolism increases, which in turn causes their heart rate to increase. The heart-body dissociation hypothesis explains more reasonably the presence of cybersickness in a motionless state than the heart-body connection hypothesis. The heart-body dissociation hypothesis states that when a person is under stress, their metabolism increases and their heart rate increases proportionally. Conventional studies [29,30] on heart rate and stress found that participants' heart rates increased when watching a video that was assigned as a stress task. In this study, we found increased heart rate (Figure 3) and cortisol level (Figure 4) in participants experiencing cybersickness. We believe that cybersickness is accompanied by stress, and heart rate increases due to the accompanying stress, which confirms the findings of previous studies. In general, it is widely known that blood pressure (Figure 5) increases as heart rate increases. However, in our study, blood pressure decreased when heart rate increased. This is because the central nervous system causes a blood pressure response [3-6] since motion sickness is an abnormal adaptation of the autonomic nervous system due to the discordance between the vestibular sense and visual perception in the central nervous system [44,45]. Therefore, we believe that the change in blood pressure that is caused by cybersickness is different from the general correlation between heart rate and blood pressure. In summary, we found that the physiological responses that can be objectively measured to indicate cybersickness are heart rate and cortisol level.

Limitations

The number of participants (n=16) was too small to generalize the physiological responses statistically, even though they were appropriate for detecting physiological responses to cybersickness. Cybersickness is known to be sensitive to gender, age, and VR adaptation (number of experiences). However, this study did not consider these variables because our purpose was to find the physiological responses that can measure cybersickness objectively among various physiological responses. Subsequent studies should consider the number of experiences, gender, age, and VR adaptation of participants in addition to the physiological responses that were found in this study.

Conclusions

We analyzed the effects of cybersickness caused by HMD-based VR content on physiological responses. Heart rate, body temperature, cortisol level, and blood pressure were measured to analyze SSQ scores and physiological responses. A total of 16 participants watched the HMD-based VR content in a seated position and without moving to ensure their concentration was only on watching the VR content, which was developed to intentionally cause cybersickness.

From the results of our analysis, the following conclusions were drawn: (1) cybersickness causes significant disorientation, and research on cybersickness should focus on factors that affect disorientation; and (2) the physiological responses that are suitable for measuring cybersickness are heart rate and cortisol. This means that heart rate and cortisol level can be used as real-time factors to objectively assess cybersickness.

Acknowledgments

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Data Availability

All data generated or analyzed during this study are included in this published article.

Conflicts of Interest

None declared.

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Abbreviations

HMD: head-mounted display
MIMS: motion-induced motion sickness
MSAQ: Motion Sickness Assessment Questionnaire
SSQ: Simulator Sickness Questionnaire
VIMS: visually induced motion sickness
VR: virtual reality

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Short Paper

Pain Assessment Using Virtual Reality Facemask During Bone Marrow Aspiration: Prospective Study Including Propensity-Matched Analysis

Lou Soret[1,2,3*], PharmD; Nicolas Gendron[1,2,3*], PharmD, PhD; Nadia Rivet[1,2,3], PharmD; Richard Chocron[4,5], MD, PhD; Laure Macraigne[1,2], PharmD; Darless Clausse[1,6,7], MD; Bernard Cholley[1,6,7], MD, PhD; Pascale Gaussem[1,2], PharmD, PhD; David M Smadja[1,2,3], PharmD, PhD; Luc Darnige[1,2,3], MD, MSc

[1]Innovative Therapies in Haemostasis, INSERM, Université Paris Cité, Paris, France
[2]Hematology department, Assistance Publique Hôpitaux de Paris-Centre-Université de Paris, Paris, France
[3]Biosurgical research lab, Carpentier Foundation, Assistance Publique Hôpitaux de Paris-Centre-Université de Paris, Paris, France
[4]PARCC, INSERM, Université Paris Cité, Paris, France
[5]Emergency Medicine Department, Georges Pompidou European Hospital, Paris, France
[6]Department of Anesthesia and Intensive Care, Georges Pompidou European Hospital, Paris, France
[7]Biosurgical Research Lab, Carpentier Foundation, Georges Pompidou European Hospital, Paris, France
[*]these authors contributed equally

Corresponding Author:
Nicolas Gendron, PharmD, PhD
Innovative Therapies in Haemostasis, INSERM
Université Paris Cité
20 rue Leblanc
Paris, 75015
France
Phone: 33 015609 39 38
Fax: 33 015609 39 33
Email: nicolas.gendron@aphp.fr

Abstract

Background: Bone marrow aspiration (BMA) is a medical procedure necessary to the diagnosis and monitoring of patients with hematological or nonhematological disorders. This procedure is considered painful, and patients are generally anxious before and during BMA.

Objective: This study assesses the effect of immersive virtual reality on pain during BMA.

Methods: This observational prospective and monocentric study enrolled 105 consecutive patients who underwent sternal BMA with lidocaine anesthesia. The study was carried on during 2 periods. First, virtual reality facemask (VRF) was proposed to all patients in the absence of exclusion criteria. During the second period, BMA was performed without the VRF. For all patients, pain intensity after the procedure was assessed using a 10-point numerical pain rating scale (NPRS). All analyses were performed on propensity score–matched cohort (with or without VRF) to evaluate efficacy on NRPS levels.

Results: The final matched cohort included 12 patients in the VRF group and 24 in the control group. No difference in anxiety level before BMA evaluated by the patient and by the operator was observed between groups (P=.71 and .42 respectively). No difference of NPRS was observed using VRF when compared to control group (median NPRS 3.8, IQR 2.0-6.3 vs 3.0, IQR 1.9-3.0, respectively; P=.09).

Conclusions: Our study did not prove the efficacy of VRF to reduce pain during BMA.

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KEYWORDS

bone marrow aspiration; pain assessment; virtual reality facemask; anxiety; hematology; virtual reality; VR; haematology; haematological; hematological; hematological disorder; pain; pain scale; medical procedure; bone marrow; facemask; diagnosis; monitoring; anxiety

Introduction

Bone marrow aspiration (BMA) is a standard procedure for diagnosis, staging, prognosis, and follow-up response to treatment of numerous hematologic and some nonhematologic diseases. BMA is generally carried out in adult patients without general anesthesia [1] and may be performed at different puncture sites. In France, the most common site of aspiration in adults [2] is the sternal manubrium because it is more accessible than iliac crest and may be safely performed in patients receiving anticoagulant treatment. Whatever the site of aspiration, BMA is still considered a painful procedure, and standardization of pain prevention remains a major issue. Moreover, the increase in anxiety in a clinical environment can worsen the perception of pain [3]. In a previous study, we showed that despite local anesthesia, pain scores obtained using a numerical pain rating scale (NPRS) still ranged between 2.8 and 3.5 [4]. Whatever the puncture site, the patient needs to be reassured and well informed regarding the BMA procedure to decrease anxiety and pain. Indeed, in our previous cohort, more than half of the patients were anxious or very anxious before BMA, and anxiety was found to be a major predictor of pain during the procedure. The aim of this study was to explore the effects of immersive virtual reality on BMA-associated pain scores. Indeed, this technique uses multisensory stimulation to provoke patient's immersion in a virtual environment and a state of hypnosis, which is used to facilitate anxiolysis and analgesia during some procedures [5]. Many studies demonstrated a significant reduction in pain or a reduction in procedural anxiety [6] using a virtual reality facemask (VRF). Therefore, we conducted an observational prospective and monocentric study to compare the effects of VRF on anxiety and pain in patients undergoing sternal BMA with lidocaine anesthesia.

Methods

Ethics Approval

All the patients included were informed of the research protocol by letter, allowing them to express their opposition to the use of their data, according to French legislation and the institutional review board. The study was performed in accordance with the Declaration of Helsinki and authorized by the French Data Protection Agency (CNIL-1922081), and each patient signed consent.

Overview

This observational prospective and monocentric study enrolled consecutive patients who underwent sternal BMA with 1% lidocaine anesthesia for all patients and assessed pain during this procedure. All adult patients requiring sternal BMA between December 2019 and December 2020 were enrolled at the University Hôpital Européen Georges Pompidou (Assistance Publique-Hôpitaux de Paris, France).

The study was conducted during 2 periods. During the first period, immersive virtual reality using VRF was proposed to all patients (Figure 1). The VRF medical device was an Oculus Go helmet (Healthy Mind) consisting in a 3D video and audio headset, associated with virtual reality software. Patients were offered to choose 1 out of 3 relaxing environments (Zen garden, forest, or beach). During the second period, BMA was performed without VRF. Indeed, the COVID-19 pandemic did not allow us to use the VRF because of the risk of SARS-CoV-2 infection between patients. For both study periods, exclusion criteria were patient refusal, cognitive disorders, deep sedation, or language barrier. Patients were also excluded if they received any pharmacologic type of premedication or forms of analgesia other than subcutaneous lidocaine, such as a patch of local anesthetic or if they were offered to inhale nitrous oxide/oxygen gas premix (50%/50%).

For all patients, the same questionnaire was used, as previously described [4]. Briefly, this questionnaire included the following two assessments: (1) assessment of pain intensity following the procedurepatients were asked to quantify their pain intensity during BMA using a 10-point NPRS for which a score of 0 indicates no pain and a score of 10 indicates the worst imaginable pain; and (2) assessment of the patient's anxiety before the procedurepatients were classified as nonanxious, anxious, or very anxious, both according to themselves and by the operator.

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Figure 1. Patient wearing virtual reality facemask during sternal bone marrow aspiration.

Statistical Analysis

Since it has been reported in the literature that age and sex influence pain level during BMA [7-9], and to reduce confounding biases, we used propensity score method based on logistic regression to match patients with VRF with patients without VRF on sex and age using a 1:2 ratio. The matching created a balanced data set allowing comparison. In univariate analysis, continuous and categorical data were respectively expressed as median IQR (25th to 75th percentile) and as frequencies and percentages and compared using Mann-Whitney-Wilcoxon test and Fisher exact test. Statistical analysis was performed using R studio software, including R version 3.6.3 (R Development Core Team).

Results

From December 2019 to December 2020, a total of 105 patients were enrolled (Figure 2). Of these, 19 (18.1%) patients fulfilling the exclusion criteria as well as 17 (16.1%) patients who underwent an iliac crest aspiration were excluded; 1 (1%) patient who removed the mask during procedure was excluded (failure of the procedure), and pain level was not evaluable after procedure. Finally, after age and sex matching, the final cohort included 36 patients, 24 (67%) without VRF (control group) and 12 (33%) wearing a VRF (VRF study group) during BMA.

Patient's characteristics, BMA indication, and final diagnosis for all patients in the matched cohort are presented in Table 1. Briefly, the median age of patients was 66.7 (IQR: 59.4-76.2) years. More than half of the BMAs were conducted in patients from the internal medicine department (9/36, 25%), from the nephrology department (7/36, 19%), or oncology department (7/36, 19%). Regarding the indication, 15 BMAs (42%) were performed to explore a monoclonal gammopathy, 8 (22%) for an isolated nonregenerative anemia, and 8 (22%) for a bicytopenia or a pancytopenia. Groups did not significantly differ in terms of BMA indication or diagnosis. No complications related to the procedure were recorded.

Among the various relaxing environments, 8 (66%) patients of the VRF group chose the beach, 2 (17%) the forest, and 2 (17%) Zen garden videos. Importantly, the total immersion time recorded in the VRF group was estimated at 15 minutes (IQR 12-15).

Before procedure, anxiety level did not differ between groups, regardless of whoever assessed this parameter (the patient himself or the operator). Thus, in the control group 10/24 (41.7%) patients were considered anxious, and 6/24 (25%) were considered very anxious compared to the 5/12 (41.7%) anxious and 1/12 (8.3%) very anxious patients in the VRF group (P=.71). When the patient himself evaluated anxiety level, in the control group 10/24 (45.5%) patients were anxious and 2/24 (9.1%) were very anxious, compared to the 4/12 (33.3%) anxious and 2/12 (16.7%) very anxious patients in VRF group (P=.42).

Concerning BMA-associated pain, no difference in NPRS was observed between groups (median NPRS 3.8, IQR 2.0-6.3 vs 3.0, IQR 1.9-3.0; P=.09), for the VRF and the control group, respectively).

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Figure 2. Patient flowchart. VRF: virtual reality facemask. BMA: bone marrow aspiration. *reasons for declining were for the first patient a noninterest by this technology and for the second patient a desire to see the gesture and not be distracted by virtual reality.

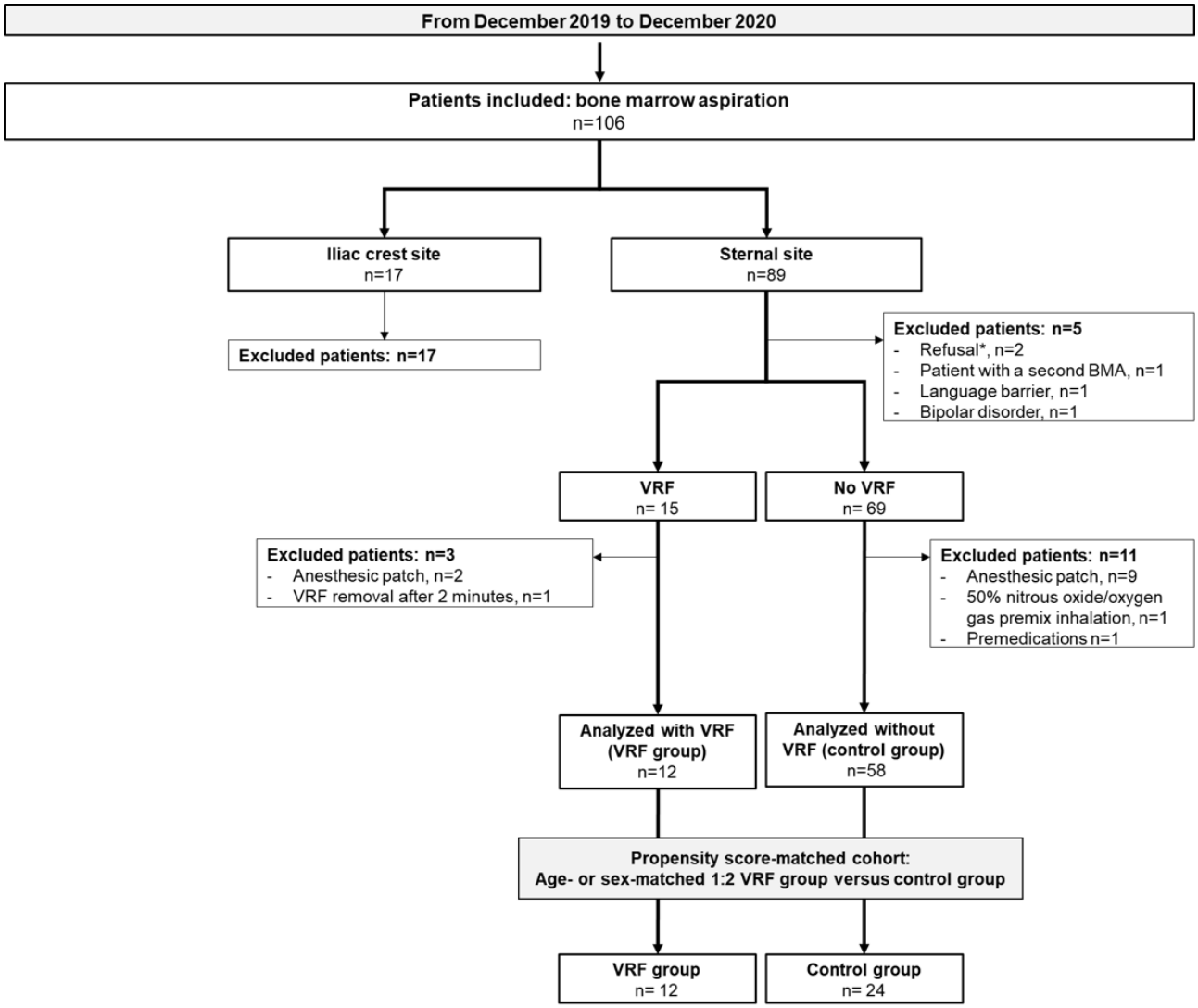

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Table 1. Patient's characteristic, bone marrow aspiration (BMA) indication, and outcomes between wearing a virtual reality mask and not wearing a virtual reality mask during BMA (N=36).

Variable	Matched cohort		*P* value
	Control group (n=24)	VRF[a] group (n=12)	
Patient characteristics			
Age (years), median (IQR)	66.4 (60.2-75.1)	66.7 (59.1-76.4)	.80
Sex, n (%)			.99
Female	11 (46)	6 (50)	
Male	13 (54)	6 (50)	
Clinical department, n (%)			<.001
Internal medicine	5 (21)	4 (33)	
Nephrology	5 (21)	2 (17)	
Oncology	4 (17)	3 (25)	
Geriatrics	2 (8)	0 (0)	
Hematology outpatients	1 (4)	0 (0)	
Surgery units	1 (4)	1 (8)	
Other departments	6 (25)	2 (17)	
BMA indication, n (%)			<.001
Suspicion monoclonal gammopathy	10 (42)	5 (42)	
Bicytopenia or pancytopenia	7 (29)	2 (17)	
Isolated nonregenerative anemia	5 (21)	3 (25)	
Thrombocytopenia	1 (4)	1 (8)	
Neutropenia	1 (4)	0 (0)	
Suspicion metastasic tumors	0 (0)	1 (8)	
Anxiety level assessed by the operator (%)			.42
Nonanxious	8 (33)	6 (50)	
Anxious	10 (42)	5 (42)	
Very anxious	6 (25)	1 (8)	
Anxiety level assessed by the patient (%)			.71
Nonanxious	10 (46)	6 (50)	
Anxious	10 (46)	4 (33)	
Very anxious	2 (9)	2 (17)	
NPRS[b] score, median (IQR)	3.0 (1.9-3.0)	3.75 (2.0-6.3)	.09
Immersion video, n (%)			N/A[c]
Forest	0 (0)	2 (17)	
Zen garden	0 (0)	2 (17)	
Beach	0 (0)	8 (66)	
Immersion time, median (IQR)	N/A	15.00 (12.0-15.0)	N/A

[a]VRF: virtual reality facemask.

[b]NPRS: numerical rating scale score.

[c]N/A: not available.

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Discussion

Principal Findings

To the best of our knowledge, this study is the first using VRF to try to reduce anxiety and pain during BMA. We did not observe any benefit of the VRF on anxiety levels before or during BMA and pain scores following BMA. We previously showed [4] that a greater level of anxiety before the procedure in patients leads to a greater sensation of pain during BMA as evaluated by the NPRS after the procedure. In this study, the VRF had no significant impact on anxiety or pain. A strength of this prospective study is that preprocedure anxiety levels were not significantly different between the two groups. Therefore, anxiety level did not impact pain assessment as we previously described [4].

The median immersion time with VRF was 15 minutes. Thus, the use of VRF could increase procedure duration, owing to the need to provide explanations to the patient and to the various manipulations for device placement and cleaning. Contrary to our findings, several studies using virtual reality therapy showed positive results in terms of reduction of pain and anxiety during medical procedures [6]. It must be mentioned that results might differ according to patient populations and indications [6].

Limitations

We acknowledge some limitations. First, the COVID-19 pandemic resulted in a premature arrest of the study, given the risk of contamination between patients using facemask, thus explaining the low number of participants in the VRF group. Therefore, a larger scale and randomized study is needed to confirm our results. Second, sternal BMA is far from being the most common puncture site used worldwide [1]. However, the sternal site is often chosen when BMA is not associated with a bone marrow biopsy. In this study, no complications related to the BMA procedure were recorded [4]. The supine position is far easier for using VRF compared with prone decubitus, which is why our study is focused on sternal BMA. Further studies need to confirm these results for iliac BMA. Third, we acknowledge that anxiety was not assessed with predefined criteria but according to the operator and the patient, as the main objective of this study was the evaluation of VRF on pain. We chose to evaluate anxiety according to our previous paper [4] to allow easier comparison of our results where anxiety was found to be a major predictor of pain during the procedure.

Finally, our cohort included only patients who did not have any BMA previously, which probably explains why patients were usually anxious about this procedure. It would be interesting to conduct a similar study on patients undergoing repeated BMA for chronic malignant hematology disease to see if the technique proves more helpful in this setting.

Conclusion

This study did not detect any benefit associated with the use of an immersive virtual reality to reduce pain and anxiety associated with sternal BMA in addition to local anesthesia.

Conflicts of Interest

None declared.

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Abbreviations

BMA: bone marrow aspiration
NPRS: numerical rating scale score
VRF: virtual reality facemask

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Original Paper

Impact of Personalized Avatars and Motion Synchrony on Embodiment and Users' Subjective Experience: Empirical Study

Myeongul Jung[1], BS; Sangyong Sim[1], MS; Jejoong Kim[2], PhD; Kwanguk Kim[1], PhD

[1]Department of Computer Science, Hanyang University, Seoul, Republic of Korea

[2]Department of Psychology, Duksung Woman's University, Seoul, Republic of Korea

Corresponding Author:
Kwanguk Kim, PhD
Department of Computer Science
Hanyang University
222, Wangsimni-ro, Seongdong-gu
Seoul, 04763
Republic of Korea
Phone: 82 222202319
Email: kenny@hanyang.ac.kr

Abstract

Background: Embodiment through a virtual avatar is a key element for people to feel that they are in the virtual world.

Objective: This study aimed to elucidate the interaction between 2 methods of eliciting embodiment through a virtual avatar: motion synchronization and appearance similarity between a human and avatar, to understand embodiment (agency, body ownership, and self-location) and subjective experience (presence, simulator sickness, and emotion) in virtual reality.

Methods: Using a full-body motion capture system, 24 participants experienced their virtual avatars with a 3D-scanned face and size-matched body from a first-person perspective. This study used a 2 (motion; sync and async) × 2 (appearance; personalized and generic) within-subject design.

Results: The results indicated that agency and body ownership increased when motion and appearance were matched, whereas self-location, presence, and emotion were affected by motion only. Interestingly, if the avatar's appearance was similar to the participants (personalized avatar), they formed an agency toward the avatar's motion that was not performed by themselves.

Conclusions: Our findings would be applicable in the field of behavioral therapy, rehabilitation, and entertainment applications, by eliciting higher agency with a personalized avatar.

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KEYWORDS

embodiment; virtual reality; virtual avatar; personalization; personalized; body motion; presence; simulator sickness; simulator; simulation; avatar; motion; body ownership; self location; agency; experience; virtual world; immersive

Introduction

Recent developments in technology have made humans citizens of the virtual world (widely known as the "metaverse"). People use virtual reality (VR) devices including head-mounted displays (HMDs) to wander around the digital world. Additionally, people use an entity such as a virtual avatar in VR to overcome limitations that their physical body cannot achieve. However, it is difficult for people to feel that they are the owner of this newly created body. This feeling of owning the body is called embodiment [1]. Embodiment consists of 3 components: body ownership (feeling that the body undergoing a certain experience is subordinate to oneself [2]), agency (feeling that "I" am the cause for body motion [2]), and self-location ("My view is located at the place where it should be" [1]).

Previous studies have found that it is possible to form a sense of embodiment toward external objects such as a rubber hand [3], virtual arm [4], and virtual body [5]. To induce this illusory feeling of embodiment, several studies [1,5-8] have used a motion-capture device for measuring a body movement and an HMD for observing a virtual avatar's actions with first-person perspective to synchronize a human activity with the movement of the virtual avatar. These studies showed that motion synchrony increased the degree of agency and found that people felt an ownership toward the virtual body used in the experiments. In addition, increased agency could make people

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feel a greater presence with less simulator sickness in VR [7]. Various studies have used the motion synchronization method to induce size perception [6] and emotion [5], as well as reduce racial bias [9].

Other studies have developed a method of enhancing embodiment by increasing appearance similarity between a real body and virtual body [10-12]. For instance, Kim et al [11] demonstrated a body size–matching method using 4 measurements of height, shoulder width, belly width, and hip width. Likewise, Gorisse et al [10] attempted to increase appearance similarity by attaching a 3D-scanned head to a virtual body, and furthermore, Waltemate et al [12] presented a "personalized avatar" by attaching a 3D-scanned head to a participant-sized body. These studies found that the more an avatar's body resembled a human's, the more people felt ownership of the virtual avatar's body [10-12]. This increment in ownership resulted in higher presence [11,12] and decreased simulator sickness [11], which could increase people's virtual experience. In line with this, Jung et al [8] showed that it is possible to measure one's body-related perception by using a virtual body resembling the individual's physical characteristics.

Although embodiment can be enhanced with motion synchrony (factor 1) and appearance similarity (factor 2), there has been little research to discover the interaction effect between these 2 factors. Kim et al [1] demonstrated that the 2 factors affected body ownership independently using a dot avatar and body size–matched avatar. Moreover, they found that the factors affecting the subcomponents of embodiment could boost each other, which can be beneficial to future applications of VR. As we can create more personalized avatars using technologies such as 3D scanning [12-14], it is worth investigating whether the boosting effect between the 2 factors would be maintained with more individualized avatars.

This study aimed to detect the effects of 2 factors (motion synchrony and appearance similarity) on embodiment and their secondary effect on virtual experiences. Our first hypothesis is that motion synchronization would increase the feeling of agency and body ownership toward the virtual body. The second hypothesis is that the appearance similarity would increase body ownership toward the virtual body. We also speculate that there are potential interactions between the 2 factors. Third, in the higher embodiment condition, the participants would have a more positive subjective experience toward VR comprising presence, simulator sickness, and emotion.

Methods

Participants

In all, 24 participants (age: mean 23.29, SD 1.97 years; female: n=12, 50%) were recruited for the study. A power analysis using PASS power analysis and sample size software (version 2019; NCSS) was run to determine sample size. All participants provided written informed consent and were compensated with US $40 for their cooperation.

Ethics Approval

All experimental protocols were approved by the Hanyang University Institutional Review Board (HYUIRB-202107-014-1). Photographed individuals in the figures provided written informed consent to publish the case details.

Hardware Setup

To generate synchrony between the participant and avatar, a motion-capture system (Motive; version 2.0.2; Natural Point) and 18 Flex 13 cameras (Natural Point) were used. Participants wore a full-body motion-capture suit with 37 reflective markers. To generate a 3D-scanned face, images of the participant's face were captured using a mobile device (iPhone SE2; Apple Inc). With the captured images, the participant's 3D face model was generated through the Metashape (Agisoft LLC) and Blender (Blender Institute) software. The virtual environment of the experiment was implemented using Unity software (version 2018.3.0f2; Unity Technologies). The software was run on a desktop PC (Windows 10 OS; Microsoft) with Intel Core i7-6700 (Intel) CPU, 16GB RAM (Samsung), and NVIDIA GeForce GTX 3070 (Nvidia) GPU.

Virtual Environment

Participants wore a motion-capture suit and HMD (HTC Vive Pro eye; HTC) to experience the virtual environment. The virtual environment was a small room, about 4 m (width) × 4 m (length) × 2.5 m (height), and a virtual mirror was set in front of the participant's location. A participant could observe the virtual avatar's body either directly through first-person perspective or by looking in the mirror. The virtual environment and experimental settings are presented in Figure 1.

Figure 1. Virtual environment (A) and experimental settings (B) of this study. (A) illustrates the virtual environment from the participant's perspective. A virtual mirror was set in front of the participant's location. (B) illustrates the experimental setting of each participant, where each participant wears a motion-capture suit with 37 reflective markers attached and a head-mounted display for observing their virtual avatar's movement in first-person perspective.

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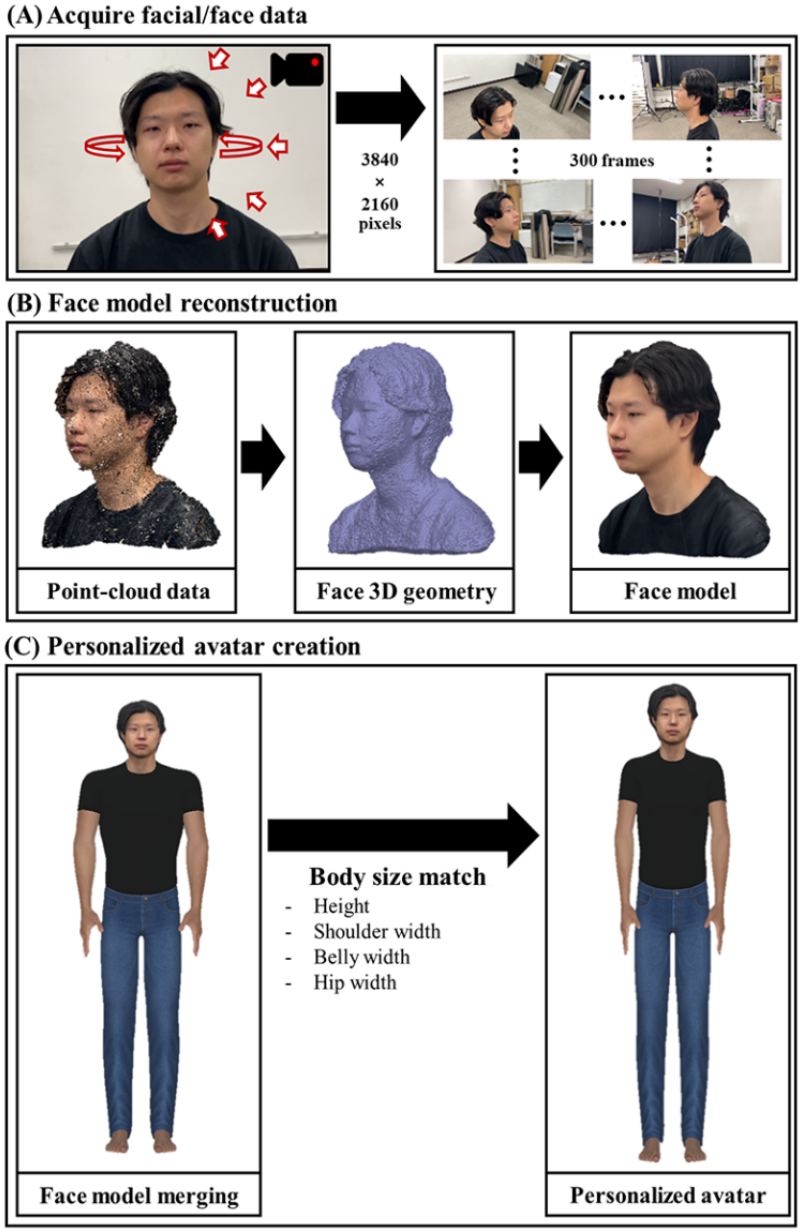
Procedures

Avatar Creation Phase

In this phase, the personalized avatar was created through the 3D scanning of participants' faces. Before the scanning, each participant completed the questionnaires for demographic information. After completing the questionnaires, the experimenter measured the participant's height, shoulder width, belly width, and hip width. They then underwent face scanning, where the experimenter recorded the participant's face while rotating around them in diverse angles for approximately 1 minute. A total of 300 frame images (3840 × 2160 pixels of resolution) of the participant's face in different angles were selected. Subsequently, images were processed by the Metashape program to build 3D point-cloud data. The point-cloud data were then simplified into 3D geometry and texture of each participant's face, and then their 3D face model was merged with an existing virtual avatar body. Finally, the participants' body sizes were applied to a virtual avatar's body to produce a personalized avatar. Figure 2 shows the process of the avatar creation.

Figure 2. Procedure for avatar creation. (A) 300 facial image data of diverse angles in 4K resolution are acquired through a mobile device. (B) Point-cloud data are extracted from the images and processed into a face model by the Metashape program. (C) Each participant's face model is merged with an avatar body, and the avatar's body size is adjusted to that of the participant.



Experimental Phase

This experiment had a 2 (motion; sync vs async) × 2 (appearance; personalized vs generic) within-subject design to examine the main effects of motion synchrony and appearance similarity and the interaction effect between them. In the motion "sync" condition, the virtual avatar's body moved according to the participant's movement, whereas in the motion "async" condition, the virtual avatar moved according to prerecorded movements, regardless of the participant's movement. For appearance similarity (or personalized appearance), a virtual avatar consisting of a participant's 3D-scanned head with a size-

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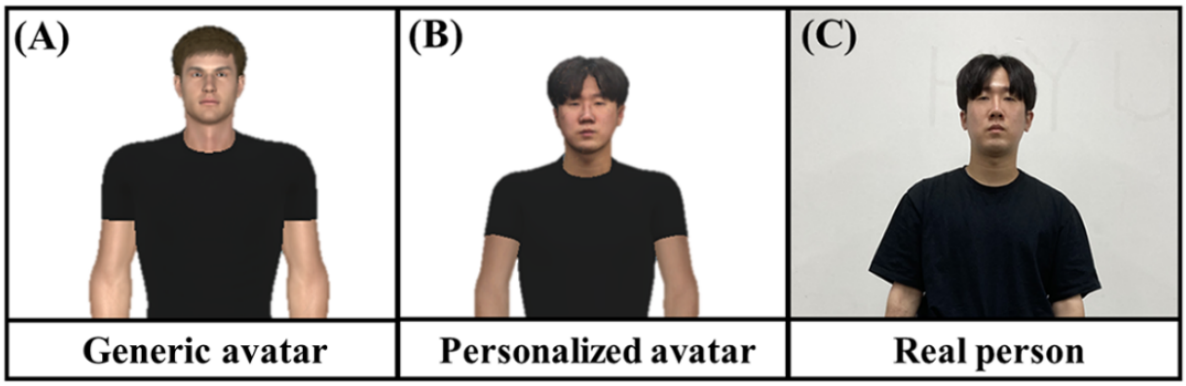
and gender-matched body was used. In the generic appearance condition, only a gender-matched avatar was used. Figure 3 shows examples of personalized and generic avatars used for a male participant.

During the experimental phase, participants underwent 4 blocks of VR experiences (ie, sync-personalized, sync-generic, async-personalized, and async-generic); the order of the blocks was counterbalanced using the Latin-square method. Participants were asked to move freely and observed a virtual avatar for 5 minutes during each block. After each block, the participants completed the similarity, embodiment, and virtual experience questionnaires listed below. Between blocks, participants rested until they felt ready to start the next block. The entire procedure lasted approximately 90 minutes.

Figure 3. Example of a (A) generic avatar and (B) personalized avatar for the (C) real person.



Dependent Measures

Similarity Questionnaire

The Similarity Questionnaire (SQ) from a recent study [13] was applied in this study. The SQ consists of four 7-point Likert scale questions assessing participants' feeling on how similar the body parts of the virtual avatar are akin to theirs. The scale ranges from –3 (fully disagree) to +3 (fully agree); Table 1 shows the 4 questions in detail. The average score of the questions was used as the similarity score.

Table 1. List of items used in the Similarity Questionnaire[a].

Question	Statement
Face	I felt the face of virtual body was similar to mine.
Torso	I felt the torso of virtual body was similar to mine.
Arms	I felt the arm of virtual body was similar to mine.
Legs	I felt the leg of virtual body was similar to mine

[a]Scale ranges from –3 (fully disagree) to +3 (fully agree).

Embodiment Questionnaire

The Embodiment Questionnaire (EQ) from recent studies [1,5,6,8,11] was modified and used in this study. The EQ consists of three 7-point Likert scale questions on agency, body ownership, and self-location. The EQ scale ranges from –3 (fully disagree) to +3 (fully agree). Each question is detailed in Table 2.

Table 2. List of items used in the Embodiment Questionnaire[a].

Question	Statement
Agency	I felt that the movement of the virtual body was caused by my own movements.
Body ownership	I felt that the virtual body I saw when looking at myself in the mirror was my own body.
Self-location	I felt that I was inside the virtual body.

[a]Scale ranges from –3 (fully disagree) to +3 (fully agree).

Virtual Experience Questionnaire

The Virtual Experience Questionnaire consisted of 3 subjective virtual experiences: presence, simulator sickness, and emotion. Participants' presence was assessed with the Presence Questionnaire [15], which consists of 21 questions using a 7-point Likert scale ranging from 1 (not at all) to 7 (completely). Participants' simulator sickness was assessed with the Simulator Sickness Questionnaire [16], which has 16 questions for checking symptoms. Each question was scored using a 4-point Likert scale ranging from 0 (not at all) to 3 (severe). Participants' emotions were assessed with the self-assessment manikin [17]. It consists of 2 subscales of arousal and valence. A visual representation of a manikin with varying levels of emotional expression was used to rate participants' emotional

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arousal, from 1 (extremely calm) to 9 (extremely excited), and valence, from 1 (extremely negative) to 9 (extremely positive).

Data Analysis

All data were analyzed using SPSS statistical software (version 27.0; IBM Corp). The evaluations of normality were performed using the skewness, kurtosis, and Kolmogorov-Smirnov tests. A 2 (sync vs async) × 2 (personalized vs generic) repeated measures ANOVA was conducted on all dependent measures to examine the effects of motion synchrony, appearance similarity, and interaction between the 2 variables. Post hoc analyses then followed. The level of statistically significant *P* value was set to .05.

Results

Similarity

The average similarity score from the SQ did not show a significant main effect for motion ($F_{1,23}$=1.448; *P*=.24; sync mean .14; async mean –.01), whereas a significant main effect was demonstrated for appearance ($F_{1,23}$=32.920; *P*<.001; η^2=.589; personalized mean .92; generic mean –.79). The interaction effect between the 2 factors was not significant ($F_{1,23}$=1.178; *P*=.29).

Embodiment

The result of embodiment is illustrated in Table 3.

Table 3. Embodiment scores of agency, body ownership, and self-location.

Embodiment, appearance	Motion		*P* value
	Sync, mean (SE)	Async, mean (SE)	
Agency			
Personalized	2.38 (.13)	–.79 (.42)	<.001
Generic	2.25 (.22)	–1.75 (.36)	<.001
Sync (personalized vs generic)	N/A[a]	N/A	.59
Async (personalized vs generic)	N/A	N/A	.02
Body ownership			
Personalized	1.54 (.20)	.00 (.41)	<.001
Generic	.96 (.33)	–1.08 (.42)	.002
Sync (personalized vs generic)	N/A	N/A	.08
Async (personalized vs generic)	N/A	N/A	.01
Self-location			
Personalized	1.58 (.26)	–.29 (.42)	<.001
Generic	1.25 (.34)	–.29 (.42)	<.001
Sync (personalized vs generic)	N/A	N/A	.22
Async (personalized vs generic)	N/A	N/A	>.99

[a]N/A: not applicable.

Agency

The agency score displayed a significant main effect for motion ($F_{1,23}$=91.653; *P*<.001; η^2=.799) and appearance ($F_{1,23}$=4.442; *P*=.046; η^2=.162). A significant interaction effect was present between the 2 factors ($F_{1,23}$=5.867; *P*=.02; η^2=.203). Post hoc analysis revealed that the participants reported higher agency in the sync condition than the async condition, regardless of appearance (personalized-sync vs personalized-async: *P*<.001; generic-sync generic-async: *P*<.001). Although the virtual avatar moved regardless of a participant's body motion in the async condition, participants felt higher agency toward the personalized avatar's movement (*P*=.02).

Body Ownership

The body ownership score exhibited a significant main effect for motion ($F_{1,23}$=22.876; *P*<.001; η^2=.499) and appearance ($F_{1,23}$=10.047; *P*=.004; η^2=.312). The interaction effect between the 2 factors was not significant ($F_{1,23}$=1.078; *P*=.31).

Self-location

The self-location score showed a significant main effect for motion ($F_{1,23}$=31.306; *P*<.001; η^2=.576); however, no main effect for appearance was found ($F_{1,23}$=.416; *P*=.53). There was no significant interaction effect between the 2 factors ($F_{1,23}$=.358; *P*=.56).

Virtual Experience

The result of virtual experience from the Virtual Experience Questionnaire is illustrated in Table 4.

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Table 4. Virtual experience scores of presence, simulator sickness, and emotion (arousal and valence).

Virtual experience, appearance	Motion		*P* value
	Sync, mean (SE)	Async, mean (SE)	
Presence			
Personalized	74.21 (2.42)	55.71 (3.68)	<.001
Generic	74.71 (3.01)	54.92 (4.00)	<.001
Sync (personalized vs generic)	N/A[a]	N/A	.77
Async (personalized vs generic)	N/A	N/A	.71
Simulator sickness			
Personalized	23.53 (5.62)	24.00 (5.46)	.86
Generic	25.09 (6.18)	27.12 (6.29)	.52
Sync (personalized vs generic)	N/A	N/A	.58
Async (personalized vs generic)	N/A	N/A	.43
Arousal			
Personalized	4.13 (.39)	4.08 (.40)	.86
Generic	3.96 (.41)	3.96 (.33)	>.99
Sync (personalized vs generic)	N/A	N/A	.57
Async (personalized vs generic)	N/A	N/A	.61
Valance			
Personalized	6.38 (.27)	5.63 (.37)	.004
Generic	5.75 (.31)	5.54 (.29)	.41
Sync (personalized vs generic)	N/A	N/A	.07
Async (personalized vs generic)	N/A	N/A	.81

[a]N/A: not applicable.

Presence

The presence score showed a significant main effect for motion ($F_{1,23}$=40.126; P<.001; η^2=.636) but not for appearance ($F_{1,23}$=.009; P=.93). Furthermore, the interaction effect between the 2 factors was not significant ($F_{1,23}$=.333; P=.57).

Simulator Sickness

The main effects of motion ($F_{1,23}$=.247; P=.62) and appearance were not significant ($F_{1,23}$=.608; P=.44). Additionally, the interaction effect between the 2 factors was not significant ($F_{1,23}$=.269; P=.61).

Emotion

Arousal did not indicate a significant main effect for motion ($F_{1,23}$=.023; P=.88) or appearance ($F_{1,23}$=.495; P=.49). There was no significant interaction effect between the 2 factors ($F_{1,23}$=.016; P=.90).

Valence showed a significant main effect for motion ($F_{1,23}$=6.111; P=.02; η^2=.210) and no main effect for appearance ($F_{1,23}$=1.325; P=.26). There was no significant interaction effect between the 2 factors ($F_{1,23}$=3.524; P=.07).

Discussion

Principal Findings

This study investigated the effects of motion synchronization and appearance similarity on participants' embodiment, perceived similarity, and subjective experience in VR. The results showed that participants experienced a higher level of agency and body ownership when body motion was synchronized and appearance was similar to theirs. Surprisingly, under the motion and appearance synchronizations, participants reported that the body motion of the virtual avatar was driven by them even when the virtual avatar moved independently, suggesting that the personalized appearance of the virtual avatar's body can create an illusory agency toward the avatar's movement that was not performed by the participant. Furthermore, our results indicated that the synchronization of motion could contribute to higher presence and induce more positive emotion.

Two novel findings on embodiment can be listed from the results of this study. First, there was a statistically significant interaction between motion and appearance on agency (significant difference between async-personalized and async-generic conditions in agency). Prior studies have reported that synchronizing motion [1,5-7] could contribute to form a higher level of agency. Results from this study support such previous

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findings, proving that the integration of visual-motion synchronization, which fulfills proprioception [18], forms a feeling that "I am the only cause of the avatar's body motion" [1]. In addition to this finding, this study demonstrated that agency was associated with body motion that was not caused by the participant; therefore, the body motion could be felt as the participant's movement when the virtual avatar resembled the participant's appearance. This kind of attribution of behavior toward oneself has been shown in several previous studies. For example, Aymerich-Franch et al [19] reported that participants felt shame and guilt for the misbehavior of a humanoid robot, which they did not perform. Likewise, Jun et al [5] reported that participants' emotions changed to happy, neutral, and sad according to a virtual avatar's emotional status. Furthermore, this study extends previous findings that body movement can be attributed to oneself with a personalized avatar. In the motion sync condition, however, the agency difference was not significant between the personalized and generic avatars. We speculate that the reason behind this finding is a higher agency score (average score of 2.31 out 3), which might have caused a ceiling effect. The current result can be used in the field of cognitive behavioral therapy, such as behavior modeling, which involves observing others to learn desirable behaviors. Using a personalized avatar, which facilitates more agency toward the avatar's action, can be more effective compared to using general avatars in behavior modeling.

Second, it was evident that the 2 factors (ie, motion and appearance) in this study affected body ownership independently. Prior studies have found that synchronizing motion [11] and personalized avatars [1,10-12] could contribute to form a higher level of body ownership. The current findings support previous studies by showing that the integration of motion synchronization [1] and visual aspects with higher fidelity [10] form a feeling that the body is one's own. Prior studies have revealed that the level of visual fidelity increased in the order of point-light avatar [1], robot avatar [10], human avatar [5], size matched avatar [11], and 3D-scanned avatar [12]. This study extends these previous findings by revealing that body ownership can be further increased with a avatar that has a 3D-scanned face and size-matched body.

In addition, it was evident that the factors of subjective virtual experience (ie, presence, simulator sickness, and emotion) were affected by motion synchrony. This result supports previous studies that confirmed higher presence [1,11] and positive emotion [1,5] by motion synchronization. Furthermore, a moderate interaction between appearance similarity (personalized vs generic) and motion synchrony (sync vs async) in emotional valence (significant difference between sync and async in personalized avatar, whereas no difference in generic avatar condition in valence; Table 4) showed that motion synchronization with a personalized avatar could induce more positive emotions than a generic avatar. On the contrary, the effect on arousal and simulator sickness was not significant. Low arousal scores across the conditions suggest that the participants were in a calm state during the experimental tasks. We speculate that low arousal might have affected simulator sickness, resulting in a floor effect across conditions.

In addition to the main findings addressed above, it is worth noting the methodology we used for generating personalized avatars in this study. In fact, many prior studies have attempted to create personalized avatars by 3D scanning a participant's face and body [2,10,12,14]. However, due to complex settings such as red-green-blue-depth camera [14] or multiple time-synchronized red-green-blue cameras [12,13], it is challenging to use this methodology to construct a personalized avatar; thus, it is not appropriate for general use. Inspired by Gorisse et al [10] and Jung et al [8], our study proposed a more convenient method for creating a personalized avatar using a single smartphone and body-size measuring. The result from the SQ showed that our method could enhance a feeling of appearance similarity between the person and avatar. Thus, in future metaverse applications, each user can easily generate their personalized avatar using their smartphone to dive into VR.

There are a few limitations in this study. First, the participants were restricted to healthy young adults. Future studies should consider recruiting participants across diverse age groups and health statuses. Second, as the prerecorded animation of the async condition consisted of simple body movements that can be performed easily by the participants, it would be stimulating to use a body motion that is "impossible" to perform to generalize the effect of appearance similarity on agency in the follow-up studies. Third, this study asked participants to move freely in the main task and measured arousal and valence as emotional variables. Although appearance similarity did not affect participants' emotions, future studies should consider participants who have negative feelings toward their body, such as individuals with eating disorders [20]. An attitude toward one's body should be considered for future medical applications.

Conclusion

This study proposed a method for creating personalized avatars using a single smartphone camera and an avatar's body size manipulation. Furthermore, this study's result indicated that participants perceived that the virtual avatar's appearance was similar to them. Furthermore, participants established a higher sense of embodiment toward the virtual avatar's body that was similar to theirs in body motion and appearance. Moreover, we discovered that the synchronization of appearance could result in a sense of agency toward an avatar's movement. We hope that the findings in the current study can contribute to the fields of physical activity promotion [21], social cognition training [22], and pain intervention [23], suggesting that matching body motion and appearance can enhance the VR experience.

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Conflicts of Interest

None declared.

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Abbreviations

EQ: Embodiment Questionnaire
HMD: head-mounted display
SQ: Similarity Questionnaire
VR: virtual reality

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Original Paper

Parental Factors Associated With Internet Gaming Disorder Among First-Year High School Students: Longitudinal Study

Rui She[1,2*], PhD; Youmin Zhang[2*], MPH; Xue Yang[2], MPhil, PhD

[1]Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong, China

[2]The Jockey Club School of Public Health and Primary Care, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China

[*]these authors contributed equally

Corresponding Author:
Xue Yang, MPhil, PhD
The Jockey Club School of Public Health and Primary Care
Faculty of Medicine
The Chinese University of Hong Kong
5/F, Ngan Shing Street, Shatin
Hong Kong, HKG
China
Phone: 852 2647 5108
Email: sherryxueyang@cuhk.edu.hk

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Abstract

Background: Parents play central roles in adolescents' socialization, behavioral development, and health, including the development of internet gaming disorder (IGD). However, longitudinal research on the parental predictors of adolescent IGD is limited.

Objective: This study aimed to investigate the reciprocal associations between various parental factors and adolescent IGD using 2-wave cross-lagged models.

Methods: A sample of 1200 year-one high school students in central China completed a baseline assessment in 2018 (mean age 15.6 years; 633/1200, 52.8% male) and a follow-up survey in 2019. IGD was measured using the 9-item DSM-5 IGD Symptoms checklist. Perceptions related to parental variables, including psychological control, parental abuse, parental support, and the parent-child relationship, were also collected from the adolescents.

Results: Of all the participants, 12.4% (148/1200) and 11.7% (140/1200) were classified as having IGD at baseline (T1) and follow-up (T2), respectively. All 4 cross-lagged models fit the data well (range for the comparative fit index .91-.95; range for the standardized root mean square residual .05-.06). Parental support (β=–.06, *P*=.02) and parental abuse (β=.08, *P*=.002) at T1 predicted IGD symptoms at T2, while parental psychological control (β=.03, *P*=.25) and a positive relationship with parents (β=–.05, *P*=.07) at T1 had nonsignificant effects on IGD symptoms at T2, when controlling for background variables. In addition, IGD symptoms at T1 did not predict parental factors at T2.

Conclusions: The findings suggest that parental factors may be significant predictors of adolescent IGD. Health interventions should consider involving parents to increase the effectiveness of treatment to prevent and reduce adolescent IGD.

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KEYWORDS

internet gaming disorder; adolescents; parental factors; longitudinal study; parenting; gaming; gaming disorder; health intervention; treatment; mental health

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Introduction

Background

Problematic internet gaming has become increasingly common with the development of technological progress. Internet gaming disorder (IGD) has been identified in the Diagnostic and Statistical Manual, Fifth Edition (DSM-5) as a condition warranting further research before including it as a formal disorder [1]. In the 11th Edition of the International Classification of Diseases and Related Health Problems (ICD-11) released in February 2022, gaming disorder (both online and offline) is defined as a disorder characterized by 3 criteria: impaired control over gaming, increased priority given to gaming, and continuation or escalation of gaming despite the occurrence of negative consequences for at least 12 months [2]. Compared with adults, adolescents are especially vulnerable to IGD because of their immature cognitive control and lack of proper coping techniques [3]. Adolescence is a period full of stressful challenges involving extensive physical, psychosocial, and interpersonal changes, which might also predispose individuals to the risk of IGD [4]. Such challenges could be intensified for first-year students entering high school, a time when they also have less academic stress and more time on the internet [5]. First-year high school students have reported a higher prevalence of IGD than their counterparts in higher grades [6]. IGD has been widely reported to affect adolescents' mental and physical health and lead to negative consequences, such as academic failure, poor sleep quality, social anxiety, and sedentary lifestyles [7-9]. As the adverse effects of addictive behavior (eg, IGD) may continue throughout adulthood, it is essential to clarify the determinants of adolescent IGD to inform effective prevention and intervention programs.

Family and parents play central roles in adolescents' socialization, behavioral development, and health. Parents behave as models for their children, engage in activities with them, monitor their children's behaviors, and provide support and encouragement that can result in behavioral change and positive health outcomes [10]. Notably, the Chinese culture is influenced by the traditional Confucian philosophy, which emphasizes children's full respect and obedience toward their parents, leading to more parental psychological control practices in the Chinese culture. Thus, parental factors could be especially prominent in the development of IGD among Chinese adolescents, such as parental modeling of online gaming, parental control, family relationships, and functioning [11]. Additionally, many child development theories (eg, transactional model and social coercion theory) suggest that parent-child influences may be bidirectional, as child development reflects continuous dynamic interactions of the child and his or her social settings, including their interactions with parents [12,13]. Therefore, adolescents' internet gaming behavior may also affect parents' responses, parents' behavior, and their relationship with their parents. However, previous studies have largely comprised cross-sectional designs and rarely examined the bidirectional associations between parental factors and adolescent IGD. In this longitudinal study, we examined the reciprocal relationships between 4 parental factors (ie, parental psychological control, parental abuse, parental support, and parent-child relationship) and adolescent IGD.

Parental Factors and IGD

A number of empirical studies have suggested that parental psychological control is associated with an increased risk of IGD [11,14-16]. Parental psychological control refers to the use of pressure to control children's behavior by overly regulating their thoughts or feelings, which interferes with their ability to develop identity and autonomy [14]. According to self-determination theory, humans have basic psychological needs for competence, autonomy, and relatedness that are essential for optimal development and functioning [17]. Parental psychological control may intrude upon children's basic psychological needs, especially for autonomy, which could result in a tendency toward excessive use of online games to satisfy those needs [18]. In addition to psychological control, some studies have indicated that parental abuse may be more prevalent in Chinese versus Western families, which was associated with more adolescent risky behaviors [19,20]. We only identified 1 cross-sectional study reporting that parental physical and verbal abuse was positively associated with IGD [11].

In contrast, parental support and good parent-adolescent relationships are protective factors against adolescent IGD [11,14,15], as they reduce stress, facilitate adaptive coping, and prevent adolescents from unhealthy behaviors [21]. Recent studies indicated that individuals with IGD evaluated their family functioning and cohesion more negatively than nonaddicted individuals [22]. For instance, 3 longitudinal studies showed that better parent-child relationships and social support could protect adolescents from developing problematic gaming behaviors [23-25], although 1 study with university students in Macao reported that social support including family support did not predict IGD at follow-up [26].

Bidirectional Associations Between Parental Factors and IGD

It is also likely that adolescent behavior problems (eg, IGD) can arouse family conflict and lead to decreased parental support [27]. Parents might practice less monitoring when they feel that their adolescents can control their online activities, which implies that the causality between parental control and IGD might go in both directions [28]. However, longitudinal data on how adolescent IGD contributes to parent-child interactions are inadequate. A few studies have investigated bidirectional associations between parental factors and IGD, suggesting that IGD symptoms elicit ineffective or negative parental responses, which may further exacerbate problematic gaming. Two longitudinal studies demonstrated a reciprocal association between parental behavior or psychological control and IGD among Chinese adolescents [18,23], whereas other studies reported unidirectional associations between adolescent IGD and parental anxiety and between parental attachment and adolescent IGD instead of bidirectional associations [29,30]. Given the mixed findings in the literature, more longitudinal studies to disentangle the relationship between various parental factors and adolescent IGD are greatly warranted to fill the knowledge gap.

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This Study

In this longitudinal study, we aimed to investigate the relationships between a wide range of parental variables (ie, parental psychological control, parental support, parent-child relationship, and verbal or physical abuse by parents) and IGD among Chinese adolescents in their first year of high school. It was hypothesized that (1) a positive relationship with parents and parental support would negatively predict adolescent IGD; (2) parental psychological control and parental abuse would positively predict adolescent IGD; and (3) IGD would predict worse parental responses to children, including a worse parent-child relationship, poorer support from parents, and more parental abuse and parental psychological control.

Methods

Study Design and Participants

This study included a convenience sample recruited from 4 high schools in Kaifeng, Henan province in China. The inclusion criteria were (1) first-year high school students, (2) willing to participate in the baseline and follow-up studies, and (3) Chinese speakers. The baseline survey was conducted during the first year of high school for participants in 2018 (T1), while the 1-year follow-up survey (T2) was conducted in the second year of high school. In total, 1239 adolescents completed the baseline survey, and 1200 adolescents completed the follow-up survey (follow-up rate 96.7%); 1200 individuals with complete baseline and follow-up data were included in the final analysis.

Procedures

Participants completed a self-reported questionnaire that took about 15 minutes to complete in the classroom setting. The survey was facilitated by research assistants but in the absence of teachers. Participation was voluntary, and we guaranteed that there were no penalties for refusals. The confidentiality of the data was guaranteed, and only researchers could access the data. Information about the parent's first name and home floor number was used for data matching. No incentive was given to the participants. The study was conducted in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guideline for cohort studies.

Measures

Internet Gaming Disorder

IGD symptoms were measured using the 9-item DSM-5 IGD symptoms checklist. It is a short, user-friendly, self-report measure assessing IGD symptoms of preoccupation, tolerance, withdrawal, unsuccessful attempts to limit gaming, deception or lies about gaming, loss of interest in other activities, use despite knowledge of harm, use for escape or relief of negative mood, and harm based on DSM-5 criteria [1]. Response options include no (0) and yes (1). A higher sum score indicates a higher level of IGD symptoms. A score of 5 is taken as the cutoff point for defining probable IGD. The Chinese version has been used with Chinese adults and children, which showed good psychometric characteristics [31,32]. The scale reliability was good in the present study (Cronbach alphas of 0.76 at T1 and 0.83 at T2).

Parental Psychological Control

The perception of parental psychological control of adolescents was measured using the Chinese version of the 8-item Psychological Control Scale-Youth Self-Report [33], which has been used in previous studies among Chinese adolescents and youth [11,21]. These items evaluate 3 psychologically controlling tactics (ie, guilt induction, invalidation of feelings, and love withdrawal). Sample item includes "My mother/father is always trying to change how I feel or think about things." Participants responded on a 4-point Likert-type scale ranging from 1 (never) to 4 (always), with higher scores reflecting greater perception of parental psychological control. The Cronbach alphas of this scale were 0.79 at T1 and 0.83 at T2.

Parental Abuse

We used 2 items to measure the frequency of verbal and physical abuse by parents in the past year (ie, "How often have you been scolded or criticized by your parents" and "How often have you been physically punished by your parents") [34]. The measure has been used with adolescents in previous studies [11,34]. Its responses range from 0 (never) to 4 (always), with higher scores indicating more frequent parental abuse. The Cronbach alphas were 0.69 and 0.67, and the correlation coefficients between the 2 items were 0.50 and 0.53 (large effect size), respectively, at the 2 time points.

Parental Support

We used 4 items to assess the level of perceived emotional and instrumental support from parents. Sample items include "How much support had you received from your parents when you needed to talk with someone or needed emotional support" and "How much support had you received from your family when you needed instrumental support (eg, financial support)." Responses were rated on a 7-point Likert scale ranging from 1 (none) to 7 (tremendous). Higher scores denote higher levels of perceived parental support. These items have been used in previous studies among Chinese adolescents and adults [11,35]. The Cronbach alphas of this scale in this study were 0.78 at T1 and 0.87 at T2.

Parent-Child Relationship

The quality of the relationship between parents and children was measured using a single item (ie, "How would you rate your relationship with your parents"). The item was rated on a 10-point scale, ranging from 1 (very poor) to 10 (very good). Higher scores denote better parent-child relationships. A previous study used this measurement among Chinese adolescents [11].

Background Factors

Background information, including sex; age; whether the participant was born in Kaifeng, Henan province; living arrangement; family socioeconomic status; and parental education levels, was collected.

Statistical Analysis

SPSS 23.0 for Windows (IBM Corp, Armonk, NY) and Amos 24 were used for all statistical analyses. Descriptive statistics and correlation analyses of parental variables and IGD are

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presented. Linear regression models were performed to test the associations between background variables and IGD. The standardized coefficients (β), unstandardized coefficients (B), and corresponding 95% CIs are reported. To explore the reciprocal relationships between parental factors and IGD, a cross-lagged model was performed for each of the parental factors using the maximum likelihood method. Background variables that were significantly associated with IGD were controlled as covariates (ie, gender, single-parent family, educational level of mother). The goodness-of-model fit was assessed using the χ^2/df value, comparative fit index (CFI), Bollen incremental fit index (IFI), Tucker-Lews index (TLI), root mean square error of approximation (RMSEA), and standardized root mean square residual (SRMR). For each index, the following criteria were applied to indicate a relatively good fit between the hypothesized model and the observed data: (1) χ^2/df ratio ≤3; (2) CFI, IFI, TLI ≥0.90; (3) RMSEA, SRMR ≤0.08 [36-38]. *P* values less than .05 were considered statistically significant.

Ethical Considerations

The study procedures were carried out in accordance with the Declaration of Helsinki. The study was approved by the Survey and Behavioral Research Ethics Committee of the corresponding author's affiliation (reference #055-18). Written informed consent was obtained from the principals of all participating schools and all parents prior to data collection, and return of the completed questionnaire implied informed consent from participants.

Results

Descriptive Characteristics

The mean age of the participants was 15.6 years at baseline (T1), and about one-half of the participants (633/1200, 52.8%) were male. The majority of the participants (1035/1200, 86.3% at T1) lived with both of their parents and were from urban areas, while 62.8% (754/1200) of the participants' mothers and 65.0% (780/1200) of their fathers had obtained an educational level of college or above. More than one-half (729/1200, 60.8%) of the participants rated their family socioeconomic status as good/very good (Table 1).

Of all the participants, 12.4% (148/1200) and 11.7% (140/1200) were classified as having probable IGD at T1 and T2, respectively. Among those without IGD at T1, 7.4% (78/1052) were classified with IGD at T2 (incidence rate), while among those with IGD at T1, 58.1% (86/148) remitted to IGD at T2 (remission rate).

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Table 1. Descriptive characteristics of the participants at baseline (T1) and follow-up (T2; n=1200).

Background variables	T1	T2
Age (years), mean (SD)	15.60 (0.59)	__[a]
Gender (male), n (%)	633 (52.8)	—
Born in the investigated city, n (%)	1018 (84.8)	—
Living with, n (%)		
Father	35 (2.9)	43 (3.6)
Mother	87 (7.3)	97 (8.1)
Both	1035 (86.3)	1019 (84.9)
Neither	43 (3.6)	41 (3.4)
Single-parent family (no)	1070 (89.2)	1055 (87.9)
Family socioeconomic status, n (%)		
Very poor	4 (0.3)	16 (1.3)
Poor	28 (2.3)	28 (2.4)
Ordinary	360 (30.0)	430 (35.8)
Good	620 (51.7)	557 (46.4)
Very good	109 (9.1)	101 (8.4)
Refuse to answer	79 (6.6)	68 (5.7)
Education level (father), n (%)		
Primary school or below	25 (2.1)	—
Junior high school	122 (10.2)	—
Senior high school/vocational school	251 (20.9)	—
College	195 (16.3)	—
Undergraduate	434 (36.2)	—
Postgraduate	151 (12.6)	—
Not applicable	22 (1.8)	—
Education level (mother), n (%)		
Primary school or below	28 (2.3)	—
Junior high school	140 (11.7)	—
Senior high school/vocational school	251 (20.9)	—
College	211 (17.6)	—
Undergraduate	434 (36.2)	—
Postgraduate	109 (9.1)	—
Not applicable	27 (2.3)	—
IGD[b] (yes), n (%)	148 (12.4)	140 (11.7)
IGD score[c], mean (SD)	1.77 (2.09)	1.65 (2.27)
Parental psychological control[d], mean (SD)	2.40 (0.64)	2.50 (0.67)
Parental support[e], mean (SD)	5.20 (1.24)	5.26 (1.35)
Positive relationship with parents[f], mean (SD)	8.22 (1.94)	7.93 (2.00)
Verbal or physical abuse by parents[g], mean (SD)	1.19 (0.90)	1.19 (0.88)

[a]Not assessed.

[b]IGD: internet gaming disorder.

[c]Score ranges from 1 to 9.

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[d]Score ranges from 1 to 4.
[e]Score ranges from 1 to 7.
[f]Score ranges from 1 to 10.
[g]Score ranges from 0 to 4.

Associations Between Background Variables and Baseline IGD

Table 2 presents the associations between background factors and IGD. Female gender (β=–.14, *P*<.001) and higher maternal educational level (senior high school to college: β=–.23, *P*<.001; undergraduate or above: β=–.23, *P*<.001; reference group: junior high school or below) were negatively associated with IGD at T1. In addition, participants who lived in a single-parent family reported higher levels of IGD (β=.07; *P*=.04).

Table 2. Associations between background variables and internet gaming disorder (IGD) at baseline (T1; model statistics: R^2=.065, F_{12}=5.89, *P*<.001).

Background variables	Unstandardized coefficients		Standardized coefficient, β
	B (95% CI)	*P* value	
Gender (male vs female)	–.59 (–.84 to –.33)	<.001	–.14
Age (years)	–.07 (–.28 to .14)	.51	–.02
Living with both parents (yes vs no)	.19 (–.01 to .40)	.07	.06
Single family (yes vs no)	.46 (.02 to .91)	.04	.07
Family socioeconomic status	.03 (–.06 to .12)	.56	.02
Educational level (father)			
Junior high school or below (reference)	N/A[a]	N/A	N/A
Senior high school to college	.05 (–.42 to .51)	.84	.01
Undergraduate or above	–.17 (–.68 to .34)	.51	–.04
Not applicable	–.42 (–1.58 to .73)	.47	–.03
Educational level (mother)			
Junior high school or below (reference)	N/A	N/A	N/A
Senior high school to college	–1.00 (–1.44 to –.56)	<.001	–.23
Undergraduate or above	–.96 (–1.45 to –.48)	<.001	–.23
Not applicable	–.97 (–2.05 to .11)	.08	–.07

[a]N/A: not applicable.

Correlations Between Parental Variables and IGD

As shown in Table 3, all parental factors including parental psychological control, parental support, a positive relationship with parents, and parental abuse at T1 were significantly correlated with IGD across the 2 waves (range for the absolute value of *r*: 0.16-0.29; all *P*<.01). Meanwhile, IGD at T1 was significantly correlated with all 4 parental variables at T1 and T2 (range for the absolute value of *r*: 0.15-0.29; all *P*<.01).

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Table 3. Correlations between parental factors and internet gaming disorder (IGD).

Variable	Parental psychological control (T1[a])	Parental psychological control (T2[b])	Parental support (T1)	Parental support (T2)	Positive relationship with parents (T1)	Positive relationship with parents (T2)	Parental abuse (T1)	Parental abuse (T2)	IGD (T1)	IGD (T2)
Parental psychological control (T1)										
r	1	0.54	–0.48	–0.31	–0.52	–0.33	0.56	0.36	0.29	0.18
P value	__[c]	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Parental psychological control (T2)										
r	0.54	1	–0.33	–0.40	–0.38	–0.48	0.40	0.52	0.14	0.21
P value	<.001	—	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Parental support (T1)										
r	–0.48	–0.33	1	0.51	0.65	0.38	–0.45	–0.29	–0.25	–0.17
P value	<.001	<.001	—	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Parental support (T2)										
r	–0.31	–0.40	0.51	1	0.42	0.61	–0.35	–0.39	–0.15	–0.21
P value	<.001	<.001	<.001	—	<.001	<.001	<.001	<.001	<.001	<.001
Positive relationship with parents (T1)										
r	–0.52	–0.38	0.65	0.42	1	0.49	–0.54	–0.35	–0.28	–0.18
P value	<.001	<.001	<.001	<.001	—	<.001	<.001	<.001	<.001	<.001
Positive relationship with parents (T2)										
r	–0.33	–0.48	0.38	0.61	0.49	1	–0.33	–0.46	–0.15	–0.26
P value	<.001	<.001	<.001	<.001	<.001	—	<.001	<.001	<.001	<.001
Parental abuse (T1)										
r	0.56	0.40	–0.45	–0.35	–0.54	–0.33	1	0.53	0.26	0.21
P value	<.001	<.001	<.001	<.001	<.001	<.001	—	<.001	<.001	<.001
Parental abuse (T2)										
r	0.36	0.52	–0.29	–0.39	–0.35	–0.46	0.53	1	0.12	0.23
P value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	—	<.001	<.001
IGD (T1)										
r	0.29	0.14	–0.25	–0.15	–0.28	–0.15	0.26	0.12	1	0.49
P value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	—	<.001
IGD (T2)										
r	0.18	0.21	–0.17	–0.21	–0.18	–0.26	0.21	0.23	0.49	1
P value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	—

[a]T1: baseline.

[b]T2: follow-up.

[c]Not applicable.

Cross-Lagged Models of Parental Variables and IGD at T1 and T2

The 4 cross-lagged models for parental factors and IGD showed good model fit (Table 4).

The path coefficients are shown in Figure 1. Parental support (β=–.06, *P*=.02) at T1 significantly predicted fewer IGD symptoms at T2, and parental abuse observed at T1 (β=.08, *P*=.002) predicted a higher level of IGD symptoms at T2, whereas parental psychological control (β=.03, *P*=.25) and parental relationship (β=–.05, *P*=.07) at T1 had nonsignificant effects on IGD symptoms at T2. In addition, all the paths from IGD symptoms at T1 to parental variables at T2 were not significant.

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Table 4. Model fit indices of the 4 cross-lagged models for parental factors and internet gaming disorder (IGD).

Model	CMIN[a](χ^2)	*df*	CFI[b]	IFI[c]	RMSEA[d]	CMIN/*df*	SRMR[e]
Model 1 (Parental psychological control)	62.208	6	.937	.938	.088	10.368	0.06
Model 2 (Parental support)	79.788	7	.913	.914	.093	11.398	0.06
Model 3 (Parent-child relationship)	69.674	8	.927	.927	.080	8.709	0.06
Model 4 (Parental abuse)	64.616	9	.945	.946	.072	7.180	0.05

[a]CMIN: minimum value of the discrepancy function.

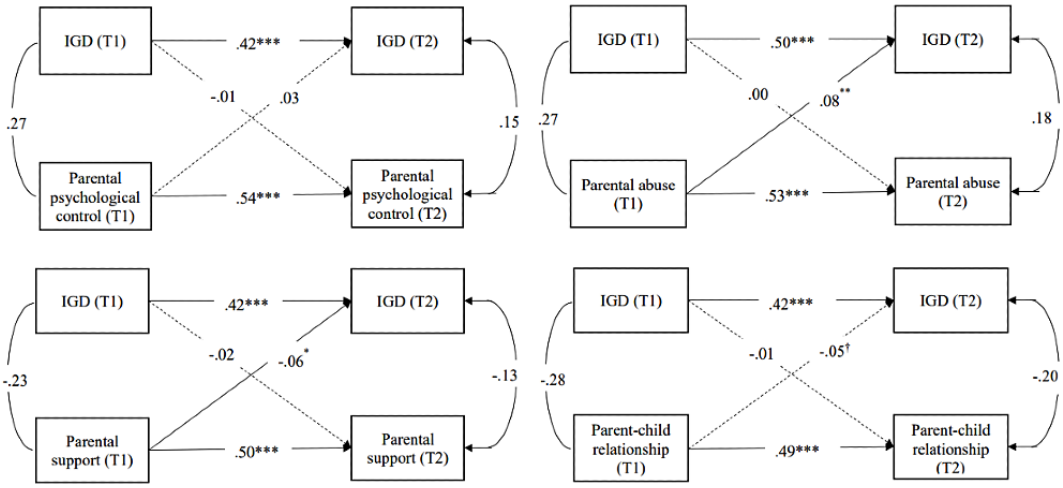
[b]CFI: comparative fit index.

[c]IFI: Bollen incremental fit index.

[d]RMSEA: root mean square error of approximation.

[e]SRMR: standardized root mean square residual.

Figure 1. Cross-lagged models of parental variables and adolescent internet gaming disorder (IGD), showing the standardized coefficients and excluding the demographic variables that were controlled in the model (ie, gender, single family, and mother's education level. **P*<.05, ***P*<.01, ****P*<.001, †.05<*P*<.1; T1: baseline; T2: follow-up.



Discussion

Principal Findings

This study represents the first longitudinal study to test the reciprocal relationships between various parental variables (ie, parental psychological control, parental support, positive relationship with parents, and parental abuse) and adolescent IGD in a large sample of Chinese first-year high school students. The results suggest that there were stable and significant cross-sectional correlations between parental factors and IGD symptoms. Furthermore, the cross-lagged effects indicate that higher levels of parental abuse positively predicted subsequent adolescent IGD symptoms, while parental support negatively predicted IGD symptoms. In contrast, there was no significant effect of IGD symptoms on predicting parental factors. The findings underline the need to tackle parental factors to prevent and reduce the risk of adolescent IGD.

We found that about 12% of the participants had probable IGD at both waves, which is comparable to the prevalence reported in previous studies among Chinese adolescents using the same measurement tool [11]. Only 52% of adolescents with probable IGD at T1 continued to have IGD at T2, suggesting that IGD symptoms may fluctuate across time. Similarly, previous studies reported low temporal stability of IGD, ranging from 20% to 50% across a 1-year period among adolescents [39]. This fluctuation may be explained by the rapid changes in biological, mental, and social status during adolescence. Such changes at this stage of life may be more frequent and have a more profound impact on one's behaviors than in other stages (eg, adulthood) [29]. In addition, higher-grade high school students may perceive more academic stress as they prepare for the National College Entrance Examination and receive more stringent supervision from their teachers and parents, resulting in less time spent on the internet and lower levels of IGD symptoms [4,40,41]. Given that longitudinal studies on IGD are relatively lacking, the stability of IGD as a disorder is still under-examined. Surveillance studies with a longer follow-up period and during the transition stage are warranted to better understand the nature and conversion rate of IGD. Consistent with prior literature, adolescents who were male and living in single-parent families reported higher levels of IGD [42,43]. In addition, higher maternal educational levels may imply a better nurturing and upbringing environment for children, which may reduce the risk of adolescent IGD. Investigation and intervention efforts targeting these disadvantaged or at-risk populations (eg, male adolescents, single-parent family, and low maternal educational level) in particular are warranted.

Interestingly, we identified 2 significant predictors of IGD (ie, parental support and parental abuse), corroborating prior

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cross-sectional and longitudinal studies [11,14-16]. Parents are often primary caregivers of adolescents and provide emotional and instrumental support. Parental support is an important resource for resilience and ability to cope with stress by adolescents; such resources can reduce their stress, facilitate adaptive coping, and prevent risk behaviors [11]. Sufficient parental support may imply a positive family environment and family functioning, which have been negatively linked to various internalized (eg, depression and suicide) and externalized (eg, risky behaviors) adolescent problems [22]. Therefore, adolescents with sufficient parental support might be less likely to rely on the virtual world (ie, the internet) to meet their basic and psychological needs (eg, sense of belonging and connection) [22]. However, adolescents who perceive low parental support might feel rejected, feel incompetent, and develop a negative evaluation of oneself that leads to low self-esteem, which in turn is associated with a higher risk of internet addiction [44]. Future studies may explore other parental and familial factors (eg, family environment and functioning) for IGD and potential mediators (eg, needs satisfaction). Notably, 24% and 6% of the participants reported that they often or always experienced parental verbal and physical abuse, respectively. Such experiences could be extremely stressful and even traumatic for adolescents, and thus, they may overly rely on internet gaming to cope with stress and escape. This may support the application of the stress coping theory to understand the development of adolescent IGD. To our best knowledge, this is the first longitudinal study that showed parental abuse may increase adolescent IGD. However, it should be noted that the effect size for the associations between parental factors and IGD was relatively small. Interpretation of the findings should be cautious, and further longitudinal studies to confirm these findings are greatly warranted.

In contrast, parental psychological control did not predict subsequent IGD symptoms. This finding is inconsistent with that of a previous longitudinal study that indicated that parental psychological control, as an overly intrusive and authoritarian parenting style, had a significant effect on adolescent IGD [18]. However, adolescents with higher levels of parental psychological control may also perceive higher pressure of behavioral control from parents and inhibition of deviant behaviors such as internet gaming [45]; thus, parental psychological control may decrease adolescent IGD. The opposite effects of parental control on IGD may result in a nonsignificant relationship between parental psychological control and IGD. However, this speculation needs further investigation by including both parental psychological control and behavioral control. In addition, we found that a positive parental relationship predicted lower IGD symptoms at T2, with marginal significance (P=.07). A previous study suggested that the mother-child relationship was a stronger predictor of adolescent internet addiction than the father-child relationship [45]. Since mothers and fathers may have different weights and roles in the parent-child relationship, the fact that we combined mother and father as a parental variable may be a limitation of this study. Therefore, further studies should differentiate mother-child and father-child relationships, which might provide a better understanding of the role of the parent-child relationship on IGD.

However, the findings suggest that adolescent IGD did not significantly predict perceived parental status. Similarly, a previous study in the Netherlands reported that parental communication, reaction, and rules regarding internet use helped prevent children's compulsive internet use, whereas compulsive internet use did not predict changes in parental communication and reactions toward children's internet use [46]. The nonsignificant findings may not ascertain that adolescent IGD is not important in the family environment and parental-child relationship; a few emerging studies have suggested that excessive gaming may displace opportunities for family interaction [22]. It is plausible that the status of the family environment and parent-child relationship are relatively stable attributes, and a longer follow-up period may be required to observe potential changes in parental status. In addition, the effect of IGD on parental responses may be based on the prerequisite that parents are aware of their children's gaming behavior and consider it a problem. In other words, these factors may moderate the effect of adolescent IGD on parental responses, which should be assessed as confounders in future studies.

This study has several limitations. First, participants were selected based on convenience sampling from central China, which could be subject to selection bias and reduce the generalizability of findings to adolescents from other regions. Second, our results had relatively small effect sizes. Given the large sample size, associations with small effect sizes could be statistically significant (eg, weak prospective associations between parental factors and IGD); both statistical significance and effect sizes should be taken into consideration when interpreting the results. Third, the use of self-reported measures might be subject to recall bias and social desirability bias. Disclosing IGD status may be a sensitive issue for students during school-based surveys, even when anonymity is guaranteed. In addition, the variables of parent-child relationship, physical abuse, and verbal abuse were measured by single-item scales. Future studies should validate the findings with more refined measures. Future research may also consider incorporating data from multiple informants (eg, parents) and different methods (eg, qualitative interviews). Meanwhile, the Cronbach alphas for the parental abuse scale were relatively low (<0.7), which might be attributed to the limited number of items in the scale [47-49]. Fourth, as we focused on parental factors, other individual-level (eg, emotional regulation and coping) and interpersonal-level factors (eg, peers and teachers) of adolescent IGD were not investigated. Future studies may investigate the interplay of multilevel factors in the development of IGD.

Nevertheless, the findings of this study signify the need for parents to be involved in interventions for adolescents exhibiting symptoms of IGD to increase the effectiveness of treatment. Education and skill training programs for parents could increase their awareness of the potential harms of their psychological, physical, and verbal abuse on IGD for adolescents and teach them proper parenting practice (eg, positive parenting styles) and intergenerational communication (eg, nonviolent communication skills). In addition to individual-based therapy such as cognitive-behavioral and problem-solving therapy,

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family-based therapy that views children's problems from a familial or ecological perspective and helps to foster a supportive and healthy family environment may be particularly helpful. Indeed, the family-based approach has shown efficacy in reducing the risk of IGD. For instance, multi-family group therapy, which involves reducing high and unreasonable expectations and criticism by parents and identifying alternative ways for adolescents to satisfy needs for competence and relatedness, has effectively reduced the rate of gaming problems among Chinese adolescents [50].

Conclusions

This study indicates that parental support and parental abuse were salient predictors of adolescent IGD. However, the longitudinal effect of IGD on parental factors was nonsignificant. These findings enhance the understanding of the prospective associations between parental factors and adolescent IGD in the Chinese context and demonstrate the value of fostering positive family dynamics and environment in adolescent IGD interventions.

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Authors' Contributions

RS and YZ conceptualized the study, designed the methodology, performed the investigation, curated the data, and performed the formal analysis. RS and XY wrote, reviewed, and edited the manuscript. XY acquired funding. YZ wrote the original manuscript draft. All authors commented on previous versions of the manuscript and approved the final manuscript.

Conflicts of Interest

None declared.

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Abbreviations

CFI: comparative fit index
DSM-5: Diagnostic and Statistical Manual, Fifth Edition
ICD: International Classification of Diseases and Related Health Problems
IFI: incremental fit index
IGD: internet gaming disorder
RMSEA: root mean square error of approximation
SRMR: standardized root mean square residual
STROBE: Strengthening the Reporting of Observational Studies in Epidemiology
TLI: Tucker-Lews index

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Corrigenda and Addenda

Correction: Development of a Therapeutic Video Game With the MDA Framework to Decrease Anxiety in Preschool-Aged Children With Acute Lymphoblastic Leukemia: Mixed Methods Approach

Dai-Jie Yang[1,2], RN, MSN; Meng-Yao Lu[3], MD; Chi-Wen Chen[1], RN, PhD; Pei-Ching Liu[1], RN, PhD; I-Ching Hou[1,4], RN, PhD

[1]College of Nursing, National Yang Ming Chiao Tung University, Taipei City, Taiwan
[2]Department of Nursing, National Taiwan University Hospital, Taipei City, Taiwan
[3]Department of Pediatrics, National Taiwan University Hospital, Taipei City, Taiwan
[4]Efficient Smart Care Research Center, National Yang Ming Chiao Tung University, Taipei, Taiwan

Corresponding Author:
I-Ching Hou, RN, PhD
College of Nursing
National Yang Ming Chiao Tung University
Number 155, Section 2, Linong Street
Beitou District
Taipei City, 11221
Taiwan
Phone: 886 28267000 ext 67315
Email: evidta@gmail.com

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In “Development of a Therapeutic Video Game With the MDA Framework to Decrease Anxiety in Preschool-Aged Children With Acute Lymphoblastic Leukemia: Mixed Methods Approach” (JMIR Serious Games 2022;10(3):e37079) the authors noted a few errors in Table 3.

In the originally published paper, the headings of subcolumns appeared as “FRS score, range” and “FRS score, mean (SD).” These headings have been corrected to “Range” and “Mean (SD),” respectively. The sequence of footnotes was revised accordingly. The updated version of Table 3 can be viewed below. The originally published Table 3 is in Multimedia Appendix 1.

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Table 3. Caregiver-reported invasive therapies.

Invasive therapy administered	Experimental group (n=7)			Control group (n=8)			*P* value[a]
	Times administered, n (%)	Range	Mean (SD)	Times administered, n (%)	Range	Mean (SD)	
IM[b] injection (buttocks injection)	25 (37)	1-5	3.5 (1.6)	27 (39)	0-6	3.9 (1.3)	.81
PORT[c] puncture	17 (25)	0-6	2.8 (1.9)	18 (26)	1-4	2.3 (1.0)	.90
IV[d] injection	13 (19)	1-6	1.9 (1.9)	13 (19)	0-3	2.1 (0.4)	.50
IT[e] injection	6 (9)	0-2	2 (0)	8 (12)	0-2	1.1 (0.4)	.66
BMA[f]	4 (6)	0-2	2 (0)	3 (4)	0-2	1.5 (0.7)	.77
BT[g]	2 (3)	0-2	2 (0)	0 (0)	0-0	0 (0)	.29
Total	67 (100)	6-15	9.6 (3.5)	69 (100)	2-11	8.6 (2.9)	>.99

[a]This *P* value was based on the Mann-Whitney *U* test.

[b]IM: intramuscular.

[c]PORT: port-a-cath catheter system.

[d]IV: intravenous.

[e]IT: intrathecal.

[f]BMA: bone marrow aspiration.

[g]BT: blood transfusion.

The correction will appear in the online version of the paper on the JMIR Publications website on October 5, 2022, together with the publication of this correction notice. Because this was made after submission to PubMed, PubMed Central, and other full-text repositories, the corrected article has also been resubmitted to those repositories.

Multimedia Appendix 1
Originally published Table 3. Caregiver-reported invasive therapies.
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Corrigenda and Addenda

Correction: Parental Factors Associated With Internet Gaming Disorder Among First-Year High School Students: Longitudinal Study

Rui She[1,2*], PhD; Youmin Zhang[2*], MPH; Xue Yang[2], MPhil, PhD

[1]Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong, China

[2]The Jockey Club School of Public Health and Primary Care, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China

[*]these authors contributed equally

Corresponding Author:
Xue Yang, MPhil, PhD
The Jockey Club School of Public Health and Primary Care
Faculty of Medicine
The Chinese University of Hong Kong
5/F, Ngan Shing Street, Shatin
Hong Kong, HKG
China
Phone: 852 2647 5108
Email: sherryxueyang@cuhk.edu.hk

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In "Parental Factors Associated With Internet Gaming Disorder Among First-Year High School Students: Longitudinal Study" (JMIR Serious Games 2022;10(4): e33806) the authors noted one error.

In the originally published article, the equal contribution note indicating that Rui She and Youmin Zhang contributed equally to the manuscript, was missed and was published as follows:

> *Rui She[1,2], PhD; Youmin Zhang[1], MPH; Xue Yang[1], MPhil, PhD*
>
> *[1]The Jockey Club School of Public Health and Primary Care, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China*
>
> *[2]Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong, China*

The author metadata has been corrected to include the 'equal contribution' footnote:

> *Rui She[1,2*], PhD; Youmin Zhang[1*], MPH; Xue Yang[1], MPhil, PhD*
>
> *[1]The Jockey Club School of Public Health and Primary Care, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China*
>
> *[2]Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong, China*
>
> *[*]these authors contributed equally*

The correction will appear in the online version of the paper on the JMIR Publications website on December 06, 2022, together with the publication of this correction notice. Because this was made after submission to PubMed, PubMed Central, and other full-text repositories, the corrected article has also been resubmitted to those repositories.

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Review

Key Stakeholders' Experiences and Perceptions of Virtual Reality for Older Adults Living With Dementia: Systematic Review and Thematic Synthesis

Aisling Flynn[1], BSc; David Healy[2], MSc; Marguerite Barry[3], PhD; Attracta Brennan[4], PhD; Sam Redfern[4], PhD; Catherine Houghton[1*], PhD; Dympna Casey[1*], PhD

[1]School of Nursing and Midwifery, Aras Moyola, Galway, Ireland
[2]School of Psychology, University of Galway, Galway, Ireland
[3]School of Information and Communication Studies, ADAPT Centre, University College Dublin, Dublin, Ireland
[4]Engineering and Informatics, University of Galway, Galway, Ireland
[*]these authors contributed equally

Corresponding Author:
Aisling Flynn, BSc
School of Nursing and Midwifery
Aras Moyola
University of Galway
Galway, H91 TK33
Ireland
Phone: 353 91493973
Email: a.flynn15@universityofgalway.ie

Abstract

Background: Technology is increasingly being used and evolving in the dementia care landscape. One such technology that has gained traction over the last decade is virtual reality (VR). VR is being applied in many areas of dementia care, including cognitive assessment and training, reminiscence therapy, music therapy, and other recreational VR applications. Despite the plethora of applications, they are often not shaped by the experiences and perceptions of older adults living with dementia. Currently, there is no qualitative evidence synthesis (QES) to explore this area. This review aimed to provide qualitative evidence supporting existing systematic reviews in this area.

Objective: The aim of this QES was to explore key stakeholders' experiences and perceptions of VR for older adults living with dementia. It aimed to explore the barriers and facilitators to VR use and provide recommendations for future design and implementation.

Methods: QES was used, which involved a systematic search of 6 databases to identify studies that qualitatively explored key stakeholders' experiences and perceptions of VR for older adults living with dementia. Thematic synthesis was used to integrate the findings of 14 studies (from 15 reports). The Critical Appraisal Skills Programme tool was used to assess the methodological quality of the included studies. The confidence placed in the review findings was assessed using the GRADE-CERQUAL (Confidence in the Evidence from Reviews of Qualitative research).

Results: A total of 15 reports from 14 studies were included in the review, consisting of a range of levels of VR immersion, stages of dementia, and care contexts. Three analytical themes were generated: stepping into virtuality, a virtual world, and returning to reality. The results indicate the importance of sensitively designing and introducing VR to this population, as older adults living with dementia often have no prior experience of using this technology. VR can be a positive experience for older adults living with dementia and can provide meaningful interactions, positive expressions, and long-term impacts on everyday functioning. However, it should be acknowledged that some negative associations must be accounted for before, during, and after use.

Conclusions: This review highlights the positive implications as well as negative associations of VR use. It emphasizes the need for VR design and implementation driven by the needs and views of older adults living with dementia as well as with other key stakeholders. Future research needs to explore the vital role that older adults living with dementia can play in the design process and how they can be empowered to meaningfully design and use this technology.

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(JMIR Serious Games 2022;10(4):e37228) doi:10.2196/37228

KEYWORDS

virtual reality; VR; dementia; experience; perception; qualitative evidence synthesis (QES); thematic synthesis

Introduction

Background

Dementia is a progressive disease characterized by the deterioration in memory, executive functioning, behavior, and everyday functioning [1]. Globally, the number of people living with dementia is rapidly increasing with an estimated 50 million people living with the condition at present [2,3]. This figure is expected to rise to 139 million in 2050. There is currently no cure for dementia or a treatment that can change the progressive nature of the disease [4,5]. A traditional medical model of practice has emphasized the role of pharmacological interventions to address the symptoms associated with dementia [6-8]. However, a shift to a more biopsychosocial model of dementia advocates for the use of nonpharmacological interventions using person-centered, wellness and enablement approaches to dementia care [8-10]. The outcomes of such interventions have been categorized by the National Institute for Health and Care Excellence as those that reduce responsive behaviors; those that maintain or improve one's functional capacity; and those that aim to reduce comorbid emotional disorders [9,11]. There is a strong evidence base to support the use of interventions such as cognitive and sensory stimulation, exercise, music therapy, reminiscence, and validation therapy [9].

Considering that there is currently no cure for dementia, strategies to support the psychosocial needs of older adults living with dementia are important. Current and emerging technologies aim to support people living with dementia throughout their disease trajectory [4,12,13]. Digital technology has been cited as a means of delivering nonpharmacological approaches to address the noncognitive aspects of dementia [14-16]. Technology-mediated nonpharmacological therapies include reminiscence and music therapy [15,17,18]. Such technologies are moving away from traditional, widely researched, passive applications, such as ambient-assisted living and monitoring systems, to more active technologies. Active applications can promote meaningful activities and include social robots, tablets, PCs, and virtual reality (VR) systems [17,19]. These more active technologies are relatively novel and underresearched in the dementia care landscape [17] but indicate promising benefits for promoting the well-being of people living with dementia [16,20]. This review focuses on VR as one such active technology.

VR is a means of relocating people to virtual places where they can participate in events and activities [21]. VR exists on a spectrum and can vary from nonimmersive VR to fully immersive systems. Nonimmersive systems often act as a "window" to the virtual world by interacting through a flat-screen PC [22,23]. Semi-immersive systems have an extended field of view that accommodates additional sensory modalities for interaction in a virtual environment (VE). Fully immersive systems are referred to as those in which the user is present in a VE using a head-mounted display (HMD) or a Cave Automatic Virtual Environment [22,23]. The hardware and software specifications can vary across levels of immersion with fully immersive systems occluding the physical world.

The distinguishing factor between VR across the spectrum of immersion and other technologies is the level of participation, where the user has the opportunity to participate in the VE rather than merely observe it [21]. VR systems operate on a spectrum of interactivity that varies depending on the aims of the user, scope of the system, and equipment used. VR experiences can be classified as passive, exploratory, and interactive [24]. Passive interaction refers to low interaction, where users have the freedom of where to look, for example, 360º video [22]. Exploratory interaction allows the user to move around the VE and the user has freedom of where to look. However, this does not accommodate touch [22]. The interactive level enables the user to "explore, control and modify" the VE [22]. This stimulates several senses and accommodates haptic feedback and interaction [22]. This review explores VR use across the spectrum of immersion and interaction, specifically in the context of people living with dementia aged >60 years.

Why Is It Important to Do This Review?

VR shows promise in its potential to provide positive experiences for older adults living with dementia. Research illustrates the impact of VR on sociability, quality of life, activities of daily living, cognitive health, and independence [25-28]. Despite the positive potential of VR, there are also negative side effects associated with its use such as simulator sickness and disorientation [29]. Although there has been a significant increase in VR use over the past decade, there is a lack of high-quality, systematic research. Although reviews have been undertaken investigating the effectiveness, feasibility, acceptability, and usability aspects of VR for older adults and people living with dementia, such reviews have mainly explored quantitative or mixed method reviews, the latter of which have typically lacked a systematic approach. No qualitative synthesis has explored the experiences and perceptions of key stakeholders such as people living with dementia, family members, health and social care professionals, and other facilitators of VR. Therefore, a systematic review and thematic synthesis is required. Qualitative evidence synthesis (QES) affords insights into the experiences and perceptions of VR from a multistakeholder perspective, thus informing future design and implementation of VR for this population [30].

Systematic reviews that use a qualitative synthesis approach are in keeping with an accelerated move beyond reviews that focus on the effectiveness to reviews that synthesize evidence related to experiential elements of certain phenomena [31,32]. The voice of people living with dementia and their caregivers are increasingly being prioritized both in research and policy to ensure results are driven by their experiences and needs [33-37]. QES can capture stakeholders' multiple perspectives

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across a range of studies, which may be lost when a study is explored in isolation or through a quantitative synthesis approach [34,35,38]. For the remainder of this paper, the term QES is used as an encompassing term for a systematic review and thematic synthesis.

How This Review Might Inform or Supplement What Is Already Known in This Area

There are several narrative and systematic reviews that provide a useful reference point for this QES, and such reviews have taken a quantitative and mixed method approach to the exploration of VR [25-28]. In such cases, VR has not focused on the full spectrum of immersion; rather, it has mainly focused on semi-immersive and fully immersive systems. This makes it difficult to draw comparisons between the various modes of delivery (ie, projectors vs HMDs). Previous reviews also lack an experiential focus, and this review aimed to explore this area qualitatively. As this is an emerging and fast-paced area, regular updated reviews are imperative to keep up to date and relevant. Reviews also vary in their exploration of the technology, with no specific focus on older adults living with dementia nor on the perspectives of other stakeholders or the spectrum of VR. Age-related factors regarding VR use vary between people living with early onset dementia and older adults with dementia. This review focuses on the experience and perceptions of VR use in the latter cohort through a multistakeholder lens [39-42] and provides design recommendations that align with the review objectives and findings of QES to supplement this area of research.

Objectives

The following are the objectives of this QES:

- To explore key stakeholders' experiences and perceptions of using VR technology for older adults living with dementia.
- To identify perceived facilitators and barriers to the use of VR technology for older adults living with dementia.
- To develop recommendations for the development of future VR experiences for older adults living with dementia.

Methods

Overview

The Effective Practice and Organization of Care protocol and review template for QES was used to guide the review process in this study [43]. This review adhered to the Enhancing Transparency of Reporting the Synthesis of Qualitative Research framework [44]. The QES protocol was registered in the International Prospective Register of Systematic Reviews (CRD42020208228) and published in a peer-reviewed journal [45].

The SPICE framework (setting, population, intervention, comparison, and evaluation) was used to determine the review question and search terms used to answer the review aims [46]. Systematic reviews were scoped to determine previously used dementia-specific and VR-related terms relevant to the review [47,48].

Criteria for Considering Studies for This Review

Types of Studies

Primary studies that used qualitative research design were included. Studies that used qualitative methods of data collection such as interviews, observations, and focus groups were eligible for inclusion. Studies that did not report primary research such as other systematic reviews were excluded. Mixed methods studies that used a qualitative method of data collection and in which qualitative data could be extracted were also eligible for inclusion. This review included those eligible studies that had been published through to October 2020. There was no starting time limit for the inclusion of studies.

Topic of Interest

The studies included key stakeholders' experiences and perceptions of VR technology use for older adults living with dementia. Data related to the qualitative discussion of the views, perceptions, or experiences of stakeholders regarding the use of VR in the results or discussion section of the studies were considered eligible. Key stakeholders related to older adults living with dementia, family members, health and social care professionals, and other facilitators of VR. VR technology for inclusion was classified as nonimmersive, semi-immersive, or fully immersive [23]. Studies from any setting such as Residential Aged Care Facilities (RACFs) and community or acute settings were eligible for inclusion.

Medical Subject Headings (MeSH)

Searches were designed in consultation with an information specialist at University of Galway. A scoping search was completed to identify suitable keywords, MeSH, and suitable literature (Multimedia Appendix 1).

Electronic Searches

A systematic search was conducted using the Scopus, Compendex, AgeLine, CINAHL, MEDLINE, and PsycINFO databases in October 2020 (Multimedia Appendix 1). Variations of search terms and MeSH terms were used according to database conventions. No year limit was applied to the search strategy.

Searching Other Resources

Additional search methods were used to avoid omitting unindexed articles [49]. Google Scholar and ProQuest were searched and the first 200 articles were screened for eligibility. Handsearching of reference lists was also performed to locate relevant articles through citation chaining. Google Scholar's "cited-by" function was used to perform a forward citation search. All records were downloaded to Endnote ×9 (Clarivate), and duplicate records were removed.

Selection of Studies

A total of 2 authors (AF and DH) independently completed 100% of title and abstract and full-text screening using the Rayyan screening software. Details of the screening process can be found in Multimedia Appendix 2. Inclusion and exclusion criteria were used to guide the screening process (Multimedia Appendix 3). Screening was completed with blinding turned on. Disagreements were resolved through consultation with a

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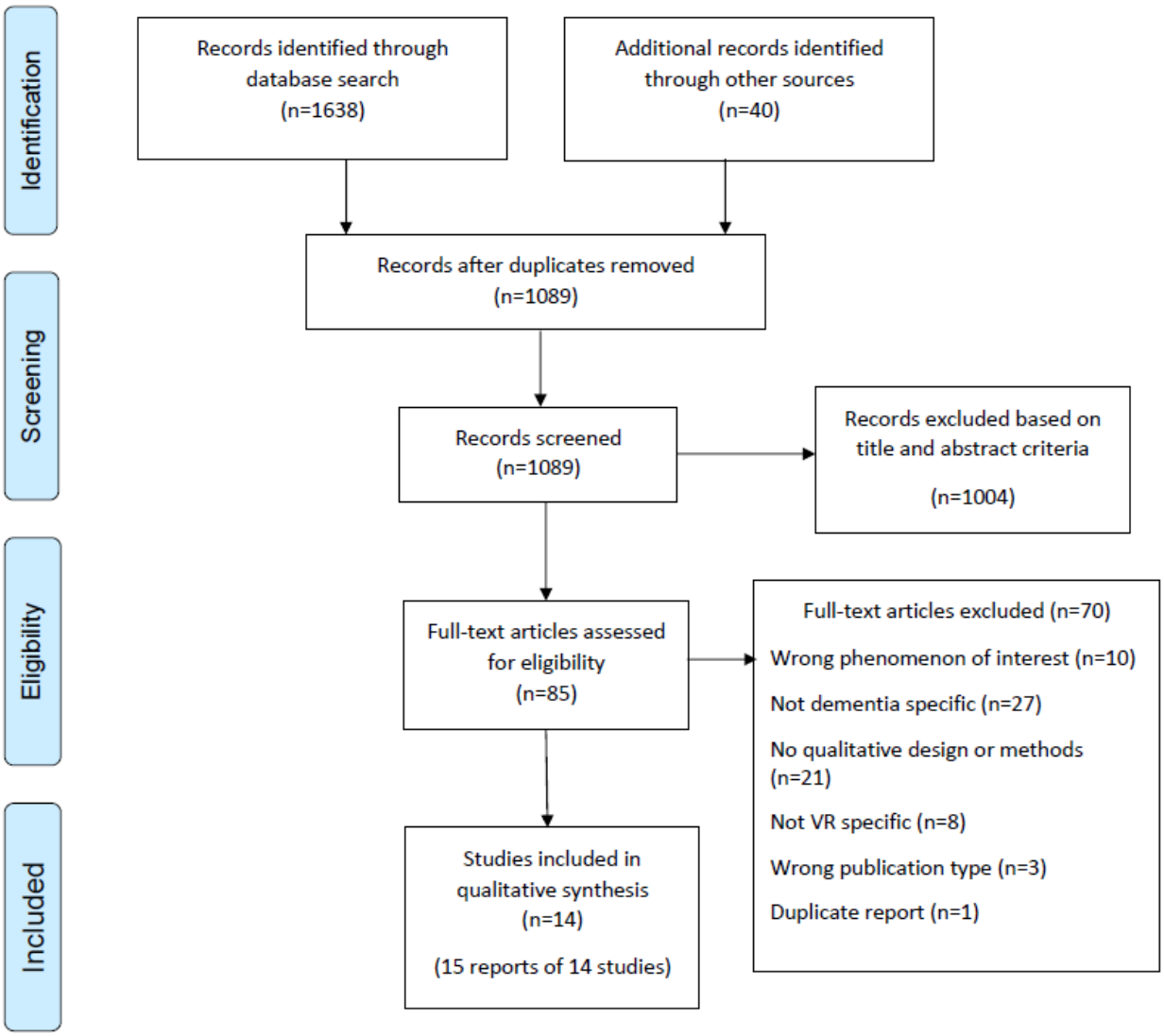
third reviewer (CH). A PRISMA (Preferred Reporting Item for Systematic Reviews and Meta-Analyses) flow diagram (Figure 1) illustrates the search results, screening process, included studies, and excluded studies with a rationale for exclusion.

Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram. VR: virtual reality.



Language Translation

The titles and abstracts that were not in the research team's native language were initially translated using Google Translate. This study did not yield any papers that required full-text translation.

Data Extraction

Two reviewers (AF and DH) completed data extraction using a bespoke form devised for this review. The form was piloted and refined by AF and DH. Data extracted for synthesis was in accordance with the approaches of Thomas and Harden [50] and Noyes et al [51], acknowledging the diversity in defining what constitutes "data" for primary qualitative studies.

For this review, data were considered as direct participant quotations and observations. Indirect findings from the authors such as observations and themes, were also extracted. Data related to the review aims were extracted. Data were not extracted in cases where studies had a broader focus or included data from adults aged <60 years without a diagnosis of dementia. Data extraction for each report can be found in Textbox 1.

All extracted data were entered into NVivo (version 12; QSR International) [52]. Data extraction was compared, and conflicts were resolved in consultation with 2 authors (DC and CH), where necessary. Details of the characteristics of the included studies can be found in Multimedia Appendix 4.

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Textbox 1. Data extraction for each report.

The following data were extracted for each report:

- Author
- Year
- Country
- Study aim
- Study design
- Key stakeholders
- Sample size
- Type of dementia
- Physical abilities of older adult with dementia
- Previous virtual reality (VR) experience
- VR use context
- Level of immersion of VR system
- Hardware specifications
- Software specifications
- Procedural aspects
- Results or findings

Assessment of Methodological Limitations of Included Studies

The methodological limitations of the included studies were assessed by 2 authors (AF and DH) using the Critical Appraisal Skills Programme Qualitative Checklist [53] (Multimedia Appendix 5). This was completed in parallel with data extraction. Disagreements were resolved through consultation with either DC or CH. Case classifications in NVivo were used to detail the study characteristics and Critical Appraisal Skills Programme responses [52].

Data Management, Analysis, and Synthesis

The RETREAT (Review question-Epistemology-Time or Timescale-Resources-Expertise-Audience and purpose-Type of Data) framework guided the authors' decision to apply thematic synthesis to the QES [54]. The framework identifies the appropriate method for QES based on the following 7 tenets: review question, epistemology, time or timescale, resources, expertise, audience, and purpose-type of data [54]. On the basis of the given criteria, thematic synthesis as per Thomas and Harden [50] was chosen for this review for several reasons: its focus on answering multiple review questions, its broad focus on a wider audience, its accommodation for both thick and thin data, and its applicability to the researcher's experience with QES.

The author followed the 3 core stages of thematic synthesis: line-by-line coding, the development of descriptive themes, and the establishment of analytical themes [50]. Line-by-line coding results in "free codes," which are then combined into descriptive themes closely related to the primary data. The analytic codes move past this descriptive element and aim to "go deeper" to address the review aims and develop a deeper level of interpretation [50,55].

The stages of thematic synthesis were managed in NVivo, resulting in an audit trail to enhance transparency [52]. One reviewer (AF) inductively coded 15 reports line by line. These codes were then organized into descriptive themes. Two reviewers (AF and CH) met to discuss the descriptive themes and agreed on how best to approach the development of the analytical themes. Focusing on the aims of the review, 1 reviewer (AF) generated analytical themes. Analytical themes were discussed and iteratively refined based on consultation with review team members (DH, DC, and CH). Furthermore, 2 people living with dementia, as part of a public and patient involvement advisory team, were given an opportunity to review the themes and provide feedback. This feedback informed the iterations of the analysis and narrative findings.

Assessing Confidence in the Review Findings

Two review authors (AF and DH) applied the GRADE-CERQual (confidence in the evidence from reviews of qualitative research) tool to assess confidence in each of the key findings [56]. GRADE-CERQual assesses confidence in evidence based on the following 4 key components: methodological limitations, coherence, adequacy, and relevance [56]. Confidence was assessed as high, moderate, low, or very low. The final assessment was based on a consensus among the review authors and in consultation with CH (Multimedia Appendices 6 and 7).

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Summary of Qualitative Findings Table and Evidence Profile

A summary of the findings and the assessment of confidence is presented in Multimedia Appendix 6 and a full evidence profile is presented in Multimedia Appendix 7.

Review Author Reflexivity

The research team came from diverse backgrounds, including occupational therapy (OT; AF), human-computer interaction (HCI) research (AF), health psychology (DH), and nursing (DC and CH). The research team members have a range of expertise and experience in the use of qualitative methods. Each member, except for one (DH), had experience working with people living with dementia in both research and clinical settings. CH and DC are experienced in the application of QES and thematic synthesis, whereas CH has extensive expertise in the use of GRADE-CERQual. CH and DC have published several QES papers focused on the area of dementia care and, therefore, have had unique insights and contributions on the complexities and pragmatic aspects of completing such reviews. Two members are conducting empirical research related to VR design for older adults (DH) and people living with dementia (AF). Two team members research VR development (SR and AB).

During screening, the team was in contact to resolve conflicts as they arose. Two members (AF and DH) completed screening, data extraction, and assessment of methodological limitations independently and were in regular contact with one another, discussing how their backgrounds in health psychology and OT influenced their decisions. An open communication process eliminated the potential bias that some members may have had when making decisions for the inclusion and exclusion of papers or deriving themes based on previous clinical and research experience.

Results

Results of the Search

A total of 15 reports of 14 studies satisfied the inclusion criteria.

Description of the Studies

These studies were conducted between 2018 and 2020. All studies used a qualitative or mixed method approach to the study design and data collection methods. However, there was variance in the reporting of the specific qualitative methodology used. Qualitative data from 6 mixed method studies were extracted. Studies were completed in Australia [57-59], the United Kingdom [60-64], Canada [65], the Netherlands [66], the United States [67], France [68], Germany [69], Cyprus [70], and South Korea [71]. Study settings included RACF [57-59,63,64,66,71], acute inpatient settings [61,62,70], community day-care settings [60,65,68,69], and hospice settings [67]. A total of 234 stakeholders were reported in the included studies, which consisted of 199 older adults living with dementia, 85 formal and informal caregivers (nursing, physiotherapy, OT, activity managers, and managerial staff), and 14 family members. It is important to note that the number of participants has not been reported in some studies. Therefore, the exact number of health and social care professionals and family members reported in this review was not representative. Such omissions were considered in relation to the overall contribution to the review findings during the GRADE-CERQual assessment [72]. Family members were also referred to as caregivers in this context.

The review included 7 fully immersive studies using HMDs and Google Cardboard [57,60-62,67,70,71]. Overall, 5 reports from 4 studies included semi-immersive systems using projectors and Microsoft Kinect [58,59,63-65]. Three studies included nonimmersive systems consisting of virtual and interactive environments displayed on a PC or television screen with interactivity supported through a mousepad and other controllers [66,68,69]. Experiences and perceptions of VR entail an array of concepts relating to the systems, including usability, acceptance, acceptability, adoption, and feasibility. Details of the characteristics of the included studies can be found in Multimedia Appendix 4.

Methodological Limitations of the Studies

A total of 15 reports were included: 8 were assessed as having no or very minor concerns [57-62,67,69], 4 studies were assessed as having moderate concerns [63,65,66,70], and 3 studies were assessed as having serious concerns [64,68,71]. Many of the included studies failed to mention important procedures and demographic information related to VR use such as informed consent procedures or the stage of dementia. A lack of reporting on the relationship between the researcher and the participants was also observed in most of the included studies. It is difficult to ascertain whether this nonreporting is a consequence of not completing certain procedures. People living with dementia are considered a vulnerable population [73,74]; thus, researchers and facilitators of VR need to work in an ethical manner to ensure transparency in the reporting of ethical procedures. The detailed rationale for the authors' decisions is presented in Multimedia Appendix 5.

Confidence in the Review Findings

GRADE-CERQual was used to assess the qualitative findings (Multimedia Appendices 6 and 7). Six findings were assessed as high confidence and 10 as moderate confidence. The findings with a moderate confidence rating exhibited concerns related to the methodological limitations and relevance of the supporting studies. Methodological concerns are related to the lack of reporting on research design, ethical procedures, and researcher reflexivity. Regarding relevance, there were disproportionate and unclear samples of older adults living with dementia, formal and informal caregivers, and other stakeholders. Despite the stakeholders providing the information, the phenomenon of interest was always related to VR use for older adults living with dementia, and there were sufficient perspectives and experiences to ensure minimal concerns regarding the adequacy and confidence in the findings. The rationale for the GRADE-CERQual assessment is provided in a summarized and full evidence profile (see Multimedia Appendices 6 and 7).

Review Findings

Three analytical themes were established to describe key stakeholders' experiences and perceptions of VR for older adults living with dementia. Analytical themes were further explained

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through several subthemes generated from descriptive themes. These findings represent a range of stakeholder views in several contexts and at different stages of dementia diagnosis. A diagram illustrating a summary of the derived themes is presented in Figure 2 and provides additional context to the findings. Table 1 and Multimedia Appendix 8 present supporting primary data from the original papers.

Figure 2. Flowchart of derived analytic and descriptive themes depicting the VR journey. VR: virtual reality.

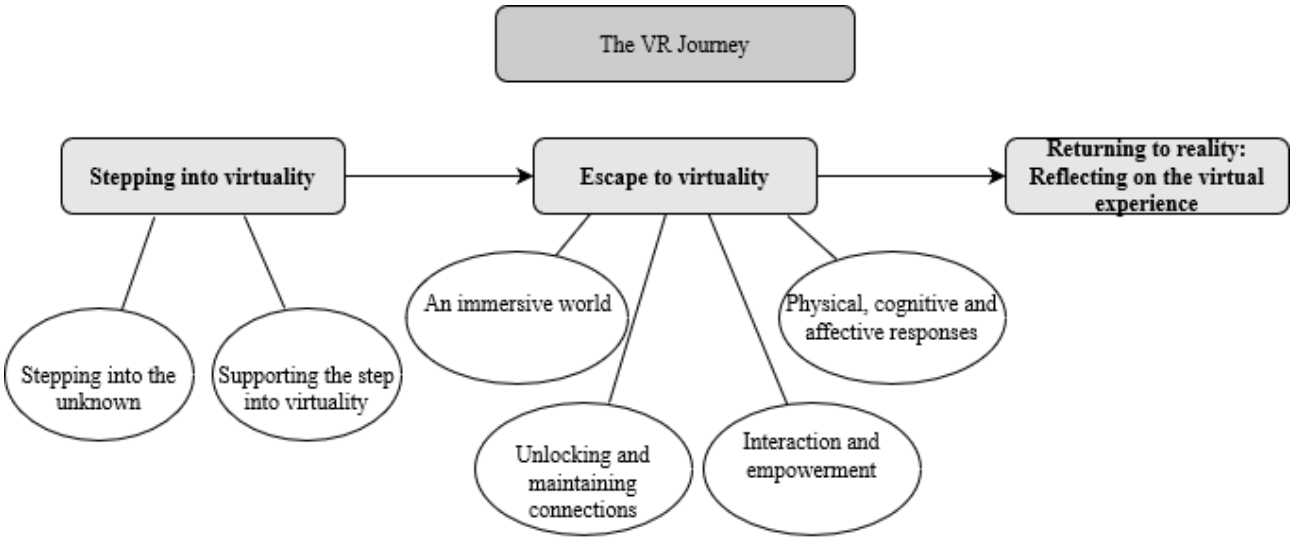

Table 1. Supporting quotations for the analytical themes and their subthemes.

Analytical theme and subtheme	Quotation
Stepping into virtuality	
Stepping into the unknown	"Caregivers were unsure whether people with dementia would try HMD[a]-VR[b] at all." [61]
Supporting the step into virtuality	"With encouragement from her daughter it seemed a lot easier to ask Lucy to try it [HMD] on" [60]; "I think by having a nurse and a physiotherapist come in, it gives a bit of reassurance for the resident" [58]
Escape to virtuality	
An immersive world	"VWs[c] [...]triggered the overall feeling of 'being in a garden'." [63]; "Most participants reported a high level of presence during the interviews, reporting that it felt 'real' or 'like they were in there'." [62]
Unlocking and maintaining connections	"VWs [virtual worlds] allow the residents to temporarily step outside of their closed physical environment of long-term care facilities and transport them to a (albeit virtual) world of reminiscence" [63]; "The interaction...because we have got two levels, those downstairs never meet people from upstairs...and they got to know each other" [58]
Interaction and empowerment	"the installation gives them a feeling of being in the control and meaningfulness." [66]; "Mum was using her hands to control the movement. It means she's got control of something in her life, that control element. What other control has she really got?" [FF6] [59]
Physical, cognitive, affective	"The majority of the residents seem to really enjoy it. I see their faces smiling, and they seem quite relaxed with it" [SF1] [59]; Post VR Observations [...] Commented, "It was the best day ever" [...] "Best day I've ever had." [PWD3, Observations, 1] [62]
Returning to reality: Reflecting on the virtual experience	
	"It's a one-time experience, you don't need it twice" [67]; When asked if she would continue to use the system after the study ended, she replied "yes, it is a good memory training and it gives it a structure to everyday life." [69]

[a]HMD: head-mounted display.

[b]VR: virtual reality.

[c]VW: virtual world.

Stepping Into Virtuality

This theme relates to stakeholders' anxieties and concerns regarding anticipation of VR use. All studies reported that older adults living with dementia had no prior experience of using VR, consolidating the need to carefully introduce VR to this population and other stakeholders such as informal and formal caregivers. The subthemes are stepping into the unknown and supporting the step into virtuality.

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Stepping Into the Unknown

This subtheme explored the concerns, worries, and anxieties experienced by older adults living with dementia and formal and informal caregivers in anticipation of VR use. Formal caregivers and family members across 4 studies reported skepticism and concerns regarding the stage of dementia, physical functioning, and its impact on enjoyment [59]; possible negative emotional impact [61]; VR being perceived as lonely or scary [61]; or preconceptions surrounding the potential disorientation, perseveration, confusion, or risk of falling while using VR. Caregivers questioned why residents could not visit physical locations rather than virtual ones. They also expressed that visiting virtual locations in VR may prompt residents to request visits to inaccessible physical locations after use. Older adults living with dementia also have concerns regarding the appearance of VR systems, leading to a refusal to try VR [70]. Those who agreed to trial the fully immersive HMD cited it as being large, intimidating, scary, and unnatural, and declined further use to avoid looking foolish and to protect their dignity [60].

To appropriately introduce VR to older adults living with dementia and their informal and formal caregivers, there is a need for adequate setup and implementation procedures to ensure eligibility, reassurance, safe setup, and use. Eligibility and safety screening were advocated by facilitators in studies to identify those most suited to VR use and accommodate their needs [58,62]. Care staff and family members gradually introduced VR to older adults living with dementia by using VR in their own bedrooms before use in a common area, showing videos and images of the system, and having time to try the headsets before sustained use [58,60]. Facilitators of VR, including researchers and care staff, noted the value of easy-to-set-up, portable hardware systems with troubleshooting guides [62]. In particular, 3 care staff members in a study reported difficulty setting up body tracking systems for those seated or using wheelchairs [59]. Two studies ensured safe reaching and rotation by positioning the equipment in the center of the tracking space [57,62].

Supporting the Step Into Virtuality

Supporting the step into virtuality subtheme explored the support and encouragement of informal and formal caregivers in providing a gateway to VR for older adults living with dementia. It explored the role of facilitators before and during VR use. Support and encouragement were manifested through verbal feedback, prompts, physical assistance, and readjustment before and during the system use. Facilitators varied across studies and included researchers, physiotherapists, nursing staff, informal caregivers, and activity coordinators.

The trusted relationship between older adults living with dementia and their caregivers served as a means of encouraging VR use [60,69]. Three studies referred to persons living with dementia requesting a family member's presence when using VR [59,69,71]. The facilitator was perceived as a vital agent in monitoring engagement, encouraging interactivity, empowering, and reassuring older adults living with dementia when using VR [58,59,71]. Through the spectrum of immersion, the facilitator adapted VR in response to observations and feedback from older adults with dementia to sustain engagement, attention, and motivation [59,62-64,70]. Verbal encouragement and feedback regarding the upcoming tasks and interactions to be completed facilitated encouragement [70]. The facilitator often asked probing questions during the activity to gauge tolerance and enjoyment and to facilitate conversations for sustained use [60,63,67,70]. Akin to monitoring safety and interaction, the facilitator played a role in monitoring how the headset and VR equipment was tolerated, often physically readjusting the headsets or repositioning the person during VR use [57,70].

Escape to Virtuality

This theme explored the experiential elements of VR use. Subthemes include an immersive world; unlocking and maintaining connections; interaction and empowerment; and physical, cognitive, and affective responses to virtuality. Subthemes mainly focused on observational data from staff and verbal feedback from older adults living with dementia and formal and informal caregivers.

An Immersive World

The included studies described the observations and verbal descriptions that indicated experiencing a sense of presence, immersion, or embodiment in the VE. This was evidenced across the spectrum of immersion, including 3 fully immersive, 2 semi-immersive, and 1 nonimmersive studies. A total of 8 older adults living with dementia in 3 studies reported VR as realistic and alluded to a sense of presence through descriptions of the content within the VEs [61-63]. Older adults living with dementia demonstrated the ability to suspend their disbelief and allow themselves to attend VEs, thus providing a sense of presence [61,62,71]. Furthermore, 3 older adults reported thinking they were cycling or rowing a boat in semi-immersive VEs [58,63]. One study noted that people living with dementia reported feeling embodied within a virtual body, whereas studies without avatars found that people living with dementia did not notice the absence of a virtual body [62]. There were instances where this sense of presence resulted in confusion between virtual and physical or real environments by one older adult living with dementia [63]. After using the system, one resident living with dementia sought trees from the VE in the physical space, illustrating its potential to exacerbate confusion [63].

Unlocking and Maintaining Connections

The unlocking and maintaining connections subtheme refers to connections established through VR use. VR served as a medium of virtual mobility or teleportation to different locations, affording older adults living with dementia opportunities to rekindle connections to their inaccessible present, past, and other individuals. The focus on person-to-person and person-to-object connections within the VE served as a medium for consolidating these connections.

Older adults living with dementia, family members, and caregivers cited VR as an escape from reality and a means to visit areas beyond their residence in the "inaccessible present" due to resource constraints and physical or cognitive decline [60-62,71]. Familiar locations and objects in the VE provided

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an excursion opportunity and connected people living with dementia to their locality or objects, such as animals [58,66].

VR enabled older adults living with dementia to experience a world of reminiscence, allowing them to connect and embrace their past across all levels of immersion [60,62,63]. Two inpatient studies noted VR as an opportunity to reproduce past events that cannot be replicated in the physical world or through routine RACF activities [62,66]. Connecting to the past sparked conversations about one's life narrative with care staff and informal caregivers by sharing old photographs, detailing their past occupations, and hobbies [64,66]. One caregiver also considered a nonimmersive system to evoke the nurturing nature of their mother [63,66]. Another study observed that a male resident with dementia recreated past experiences through movement by taking up a boxing stance in a semi-immersive environment [63].

A total of 7 studies reported that VR provided an opportunity to connect with others both within and outside their facility through engagement in mutual activities, discussion of the session, and anticipation for subsequent sessions [58,61,63,64,67,69]. Several people living with dementia used the VE content as an opportunity to talk about life experiences after VR sessions with formal and informal caregivers and other people living with dementia [60,62-64,66,69]. Two family members noted that VR provided a shared social activity in their locality, thus connecting with themselves, peers, and formal caregivers [60].

Interaction and Empowerment

Many people living with dementia interacted in VR through passive and simplistic means by observing the VE through limited interaction, naming, pointing, and discussing objects with the facilitator. Formal caregivers reported that older adults living with dementia had the ability to interact independently, provided an adequate rest period, and incorporated an appropriate level of interaction. However, 4 studies reported that older adults with dementia became confused or distracted during interactions [63,65,68,70]. The care staff in 2 studies also reported dynamic interactions across subsequent VR sessions [61,62].

When the capabilities of the person living with dementia and interactivity within the VE were in harmony, a sense of empowerment and control was experienced. This was attributed to the agency that older adults living with dementia had to freely choose their preferred environments, interactions, and movement in the VE [58,60,62,63,66,71]. Having control over the system can facilitate self-efficacy and "draw people out of themselves" to explore their unlocked capabilities [59,69], providing a new lens for caregivers to recalibrate their knowledge of the person living with dementia [61,62]. The staff reported that this agency over interactions in the VE may be the only means of control in their lives. However, when this harmonious balance was not achieved, interactions served to hinder one's sense of control [59,63]. Difficulty with interaction and a lack of control were attributed to issues such as nonintuitive button placement of the controllers [57,70], reduced dexterity and grip of older adults with dementia, inappropriate body tracking for wheelchair or seated users [57], disassociation between the controllers in the physical space and how they contributed to the VE [58], and difficulty with head movements and the tolerability of the headset [62,67,70].

Physical, Cognitive, and Affective Responses to Virtuality

The physical, cognitive, and affective responses to virtuality are related to the emotions and sensory effects of using VR. These include the enlivening effect of VR, calming effect of VR, and dynamic emotions and sensations associated with VR use. Older adults living with dementia experienced positive emotions and sensations during and after VR use.

Positive effects were reported by several formal and informal caregivers when observing older adults during VR use. Laughter [64,67,69], awe [59], positive mood [59,61,62,66], sensory stimulation, excitement, and surprise [59,61,62,66] were perceived across studies and across the immersion spectrum. A sense of enjoyment and happiness was mirrored across all levels of immersion through verbal feedback during use. However, in one study, this was captured when a person living with dementia became visibly moved and tearful [57,58,60-62,71]. Several studies observed older adults living with dementia express a positive response via song and dance through the incorporation of music into the VE [60,63,69]. The visual attractiveness and relevance of the VE have been reported to facilitate such responses [58,59,71].

Formal and informal caregivers reported VR as having a perceived positive impact on the mood, well-being, and everyday life of older adults living with dementia after VR use, as opposed to the above instances, which were during use. Family members and care staff reported lasting perceived improvements in cognition [65,66,68], memory [69], concentration [65], sustained attention [66], improved task organization [68], motivation [65,69], positive mood [60,62], reduced aggressive behaviors [62] and overall well-being [62] after the VR sessions. The specific time frame for the length of the sustained impact was not reported in the included studies. A longer-term impact was illustrated, where improvements were translated to increased engagement in activities of daily living and provided a sense of structure and purpose for older adults living with dementia. Such improvements include increased independence in dressing [65], increased motivation to exercise [62,65,69], and increased completion of kitchen tasks [68].

Caregivers also reported the negative impact of using VR. Caregivers observed confusion in one male living with dementia who wished to experience virtual content in the physical environment after VR use [66,70]. Caregivers also reported worsened behavioral and psychological symptoms of dementia [63,67], one incidence of increased hallucinations [67], and decreased mood [61,63] after use.

The sense of calm was a common thread across 7 studies both when actively interacting in the VE and when simply observing the visual and auditory content [59-62,66,67,71]. The ambient sounds and music in the VE were attributed to achieving this sense of calm by the care staff and older adults living with dementia [60,71]. Caregivers considered this "sedative effect" particularly applicable to older adults living with dementia who may become agitated. However, observational field notes in

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one study considered soothing audio or visual as inappropriate for those with apathy, and a more arousing audio and visual VE was suggested as an alternative [62,71].

Sensations related to simulator sickness, dizziness, and disorientation have been reported. Sickness during VR use was verbalized by older adults living with dementia in 1 of 7 fully immersive studies as feeling "sick" or having "a funny feeling" in their stomach [57]. Dizziness due to nonsynchronized hand and head movements was reported in one older adult living with dementia in one study [62]. Short-term disorientation was also observed when the headset was removed in 3 studies [61,67,70]. Two studies reported no sickness, dizziness, disorientation, or falls, which may be attributed to the semi-immersive and nonimmersive nature of these studies [65,68]. One fully immersive study highlighted the importance of a smooth transition back to physical space and adequate time spent in VR to avoid disorientation, sickness, and confusion [67]. Across the studies, the length of time regarding VR use varied, with no agreed length for optimal VR use [59,62,68,71].

Returning to Reality: Reflecting on the Virtual Experience

This theme explored reflections on the VR experience after returning to the physical space. Informal and formal caregivers' changing attitudes and perceptions toward the technology after observing its use are also discussed.

For those who recalled the experience, people living with dementia exhibited varied responses to VR after the session. Experiences and perceptions existed along a continuum from satisfied to neutral and to dissatisfied. Some people living with dementia and caregivers expressed dissatisfaction and unwillingness to try VR again for several reasons including boredom [59,67], lack of stimulation [59,67], disinterest in habitual use [59,71], wanting to visit the physical space [60] and the childish nature of the design [71]. This was contrasted by several older adults living with dementia who described the experience as "marvelous" [59] and something they wanted to do "over and over" [59,61,67]. Neutrality of experience was also reported, where older adults living with dementia were impartial to VR use [59,67,71]. One older adult living with dementia in hospice care disclosed "it was alright; wasn't good and wasn't bad," whereas another older adult living with dementia expressed "it's a one-time experience, you don't need it twice" [67] (p. 813). Residents in the hospice care facility study had a Functional Assessment Staging Tool score indicative of mid- to late-stage dementia, with a mean age of 85 years, which may account for this neutrality of experience.

Formal and informal caregivers reported a change in their attitude toward VR after observing older adults living with dementia using the system [61]. A care staff member in one inpatient setting reported the potential for multiuser VR to be overstimulating [63]. The care staff highlighted the need to value the age and physical functioning of older adults with dementia [59]. The variance in delivery and level of immersion across studies makes it difficult for formal caregivers to identify the optimal stage of dementia most suited to VR use [59,71].

Summary of Synthesis

This QES illustrates 3 analytic constructs demonstrating key stakeholders' experiences and perceptions of VR for older adults living with dementia throughout the VR journey. VR can be experienced positively, both momentarily and in the long term. However, the role of the facilitator is integral to achieving such outcomes and facilitating the step toward virtuality. The perception of VR varies before and after exposure to the technology, and the negative side effects of VR need to be acknowledged early in the implementation of such systems.

In addition to the thematic synthesis described in the findings section, recommendations from the primary included studies were extracted and consolidated to inform the future design of VR for older adults living with dementia. These recommendations are presented in Table 2 and categorized under different design element considerations.

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Table 2. Consolidated virtual reality design recommendations.

Proposed design element	How to achieve the design element
Design for dynamic abilities and preferences [57-64,69-71]	• Incorporate meaningful and varied scenes. Integrate items of personal relevance to stimulate conversation and engagement. • Increase interactivity without increasing the difficulty. • Design for passive and more active experiences based on the older adults' needs and abilities. • Facilitate items in the VE[a] to come to the person instead of navigating to them. • Include interactive elements, which can be adapted to increase or decrease difficulty if required. • Incorporate multiple consistent experiences, which can be changed to maintain novelty. • Avoid sensory overstimulation; present elements in the VE gradually and keep main interactable objects in the main field of view.
Everyday design [60-63,68,70]	• Design tangible interfaces with familiar items to help with understanding and interactions. • Include items in the VE, which can be associated with their semantic content.
Auditory elements [59-61,63,67]	• Include personalized or personally relevant music or sounds. • Use ambient sounds to accompany calming environments. • Incorporate adaptable volume or sound control. • Accommodate for hearing aids.
Visual elements [59,60,63,66,67,71]	• Provide feedback for tasks and next steps. • Integrate a reminder to appear before the session ending. • Clearly highlight when the session has ended. • Incorporate a range of interactable objects to avoid boredom. • Include attractive visual content using bright and contrasting colors.
Social experiences [60,62,63]	• Facilitate multiuser experiences. • Include shared activities. • Incorporate opportunities for social interaction.
Safety [57-60,62-64,68,70,71]	• Administer an eligibility assessment before use. • Identify accommodations before VR[b] use such as glasses, hearing aids, standing or seated VR, etc. • Provide adequate instruction for when VR is coming to an end and give ample time for the person to orientate themselves back to the physical space. • Ensure facilitator presence during and immediately after VR use. • Adequate frame rate and limit lagging to reduce simulator sickness. • Provide a clear timeframe for use and incorporate breaks if required. • Presence of a virtual agent in the VE to assist with interactions if required. • Ensure a smooth transition back to the physical space.

[a]VE: virtual environment.

[b]VR: virtual reality.

Discussion

Principal Findings

This thematic synthesis identified 16 key findings exploring stakeholders' experiences and perceptions of VR use by older adults living with dementia. This review reports the experiences and perceptions of older adults as self-reported by older adults living with dementia or through observations and reports of formal and informal caregivers. The findings were explored through the lens of 3 key analytic themes illustrating the VR journey. The experiences and perceptions of the spectrum of VR for older adults living with dementia have not been previously explored from a multistakeholder perspective or using QES. This review highlights the importance of conceptualizing VR use as a journey that has a clear beginning, middle, and endpoint. It is important that each stage of the "VR Journey" be sensitively introduced and facilitated with the dynamic needs of older adults living with dementia to the forefront.

Previous reviews had a limited focus on qualitative components, such as experiential, contextual, and implementation factors. This is the first known study to systematically synthesize qualitative evidence on key stakeholder experiences and perceptions across the spectrum of VR for older adults with dementia. The analysis and synthesis of the included studies suggested that VR was well-tolerated and could be a pleasant and positive experience for older adults living with dementia. Formal and informal caregivers also reported positive perceptions. This review yielded rich experiential data related to the positive effects of VR on the social and emotional well-being of older adults living with dementia, which is consistent with a similar literature review in this area [25]. The D'Cunha and Nguyen [25] review relates to broader literature reviews that explored VR use for people with sensory, cognitive, and physical health conditions who found VR to be tolerable and enjoyable [25,27,28,75] and elicited feelings of relaxation, adventure, and rejuvenation [75].

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The barriers and facilitators of VR use were encapsulated in the analytical themes of this QES and add to the existing research in this area. It is evident that the novelty of VR and its associated preconceptions acted as a barrier to its use for some older adults living with dementia. Caregivers also exhibited preconceptions that affected their willingness to implement and facilitate VR in some care settings. Such barriers were counteracted through education, training, and adequate setup procedures, as evidenced in the findings. Akin to this, support and reassurance from others were found to dissipate some of the barriers associated with VR for older adults living with dementia. Facilitators of successful VR use are also highlighted in this QES and include acknowledging concerns and worries about initial use and the need for adequate setup and facilitation for formal and informal caregivers. The negative side effects and emotions, such as fear or anxiety, discussed in this review are also consistent with previous research [27] and are highlighted by Moreno et al [76] in a systematic review of people with neurocognitive disorders, including Alzheimer disease, with adverse effects reported by a minority of participants. The Moreno et al [76] findings suggest that adverse effects are not exclusive to this population but are universal and should be monitored as with any user group [76]. Moreover, previous research has acknowledged that the diagnosis of dementia is not a barrier to the use of VR systems. However, procedures must be in place to adequately step into virtuality [77]. A meta-analysis undertaken by Kim et al [26] pointed to the need for adaptive systems and, in particular, methodology type and interaction technique that account for the sensory needs of people living with dementia [26]. Future research should consider and address these barriers and facilitators to ensure positive VR experiences for all stakeholders.

The setting also appeared to be a facilitator for VR use in several of the included studies. Baker et al [78] and Miller et al [79] explored VR use in residential and community facilities and suggested that environments with staff facilitation, Internet connectivity, and physical space may provide additional support and encouragement in terms of VR setup and other feasibility issues that may not be as apparent in the home environment. They also suggested that using VR in a home environment may be more convenient and comfortable and elicit different experiences of using the technology, particularly at the preparatory and initial stages of use [78,79].

This review provides evidence of the need to explore the importance of “in the moment” experiences versus long-term sustained outcomes. At present, evaluations have been cited as the most authentic form of data collection and reflect how a person with dementia feels at a given time [80]. VR may provide a means of being in the moment and help frame the lived experiences of people living with dementia [81]. Consistent with the findings of this review, previous empirical research [82,83] has acknowledged the lack of apparent lasting outcomes associated with VR use and stated that a lack of such outcomes should not devalue the overall experience [82,83]. Instead, the focus should be shifted to the philosophy of doing so for the moment [81,82,84,85]. Indeed, health and social care professionals are encouraged to meet people living with dementia “in” the moment, and focus on reporting the value of the present, here, and now experiences [81,84,86].

Despite VR systems being designed for single users, the social element of VR appears as a recurring thread across the included studies. It is evidenced in the literature [87-90] that designing for social connectedness is especially pertinent for people living with dementia, as they may have a reduced ability to socialize and maintain relationships. The importance of maintaining social connections was vital during COVID-19, as people living with dementia were unable to physically meet others [91-93]. This review mirrors the wider literature highlighting digital technology use as a ticket-to-talk for people living with dementia [94,95]. Syed-Abdul et al [96], and Lin et al [97] acknowledged the potential for multiuser spaces for older people living with dementia who can interact in the VE while simultaneously advocating for VR, which facilitates group participation to promote social interactions. This review supports the call for more Social VR spaces for older adults living with dementia and provides useful guidance on how this can be incorporated into future VR spaces.

The findings of this QES study highlight the value of designing VR spaces to facilitate dynamic interactions. In a previous meta-analysis, Kim et al [26] acknowledged that diverse VR functions may be perceived as too complex for older adults. This QES demonstrated that positive interactions and feelings of empowerment may be attributed to the hardware used. Furthermore, the dynamic interactions and experiences of older adults living with dementia may be attributed to the variance in hardware and software systems. The importance of considering which VR hardware is best suited for older adults living with dementia is also highlighted in this QES. Some of the included studies used realistic 360° video, which Yeo et al [98] contended may not be a representative form of the natural environment, as video content filming is completed in advance, and this limits the user’s agency over where to go. In contrast, other studies have used computer-generated VEs, which may afford more interaction, agency, and a more dynamic experience [99]. Furthermore, Strong [28] suggested that the difference between these modes of delivery may be an important factor in assessing one’s sense of immersion and presence.

This QES highlights a lack of stakeholder involvement, as most of the included studies failed to report on the VR design process. Akin to the role of stakeholders in the design process, older adults living with dementia must have their voices heard when using and evaluating VR. Most of the included studies emphasized a proxy means of data collection from health care professionals and family members rather than collecting data from the target main user, that is, older adults living with dementia. Similar to Chopra and Dixon [100], our findings advocate for people living with dementia and critical stakeholders to inform the design of VR from the outset, transcending their role beyond that of the end user of the technology. Although stakeholders may hold their own expectations and interests in the research, their views may not be consistent with, and may suppress and replace, the voice of the person with dementia [101-106]. Some advocates for the prioritization of the voices of people living with dementia use the views of secondary stakeholders as a supplement, which is

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reflected in this QES [101]. However, there is a need to consciously involve people living with dementia through innovative and strength-based methods and techniques such as the CoRTE framework, which comprises 4 main domains when conducting interviews with people living with dementia: gaining consent, maximizing responses, telling the story, and ending on a high [106-110].

The QES provides a novel overview of the spectrum of willingness to try VR in the context of various levels of immersion. Rose et al [61] found that people living with early-stage dementia reported boredom or a lack of relevance when using the VR system [61]. The question then arises as to the preference for personalized VR experiences over generic VR experiences. Hodge et al [60] and Hodge and Morrissey [86] suggested that personalized VR experiences may be more meaningful, whereas generic VR experiences may be cost-effective and offer increased transferability. A dilemma is then posed for designers, as they are faced with this dichotomy of personalized or personal relevance versus transferability. One solution may be to design for personal and contextual relevance, whereby VEs achieve a middle ground, affording older adults living with dementia the opportunity to use artifacts in the VE as a scaffold for meaningful experiences [78].

Limitations of the Review

This review adopted a broad approach to defining VR, which makes it difficult to compare across the spectrum of immersion. This is also true for the diverse implementation of VR, whereby some systems were part of an intervention, while others were once-off recreational experiences. Consistent with other reviews in the VR and gerontology landscapes, there is a lack of consistency in defining VR [111]. Thus, it was challenging to adequately identify and assess eligibility for inclusion. Search strings included the term “virtual environment” and “virtual reality” to ensure both terms, (often referred to along the reality-virtuality continuum) were utilized [111]. It should be noted that the review did not aim to identify all literature on the topic but to identify those papers “with characteristics relevant to the phenomenon being studied, not statistical representativeness” [112]. The authors acknowledge that the systematic search was completed in October 2020; thus, relevant research published after this date may be excluded from this review. The methodological limitations of the individual included studies were acknowledged in the assessment of confidence in the findings using the GRADE-CERQual.

Implications for Practice and Future Research

This review aimed to complete a systematic QES that used best practice in assessing confidence in the research findings, an approach that may complement quantitative reviews on the use of VR for older adults living with dementia, and provide insights into the contextual factors related to its use [32,113]. This QES highlights the need for additional qualitative research on VR use in older adults living with dementia. It also stipulates the need for design recommendations to inform future design and research. Additional reporting on the design process, ethical procedures, data collection methods, and researcher reflexivity is warranted. Further research on VR use for sociability outcomes is required, which should mirror current digital technology and Social VR research for the general older adult population [57,78,114-117]. These seminal works may guide future VR use for older adults living with dementia and may be adapted to accommodate the needs of this dynamic population.

Clinicians refer to the current clinical state of VR as the “Wild West” [118] because there is an apparent lack of guidance on the length and frequency of VR for people living with dementia, formal and informal caregivers, and facilitators of VR and HCI researchers [26,28,118-120]. The broader HCI literature suggests a need for coherent design knowledge and frameworks to ensure what Tabbaa, Ang [120] term as “effective, enriched and meaningful” VR spaces. The findings of this review provide several recommendations for future research (Table 2). Furthermore, the authors advocate for a designated, trained facilitator with a protected time for VR use and highlight the integral role of facilitators in encouraging VR use.

Conclusions

Considering that there is currently no cure for dementia, strategies to support the psychosocial needs of older adults living with this condition are crucial. The use of VR for older adults living with dementia is a growing area, and this review suggests that it is a promising addition to dementia care. The QES provides recommendations for future VR design and implementation. The potential positive effects of VR use include a sense of connection, empowerment, immersion, calmness, and enlivenment. However, the potential negative implications of VR use must be considered, such as simulator sickness, fatigue, and disorientation. Moreover, the optimal hardware, software, and dosage best suited to older adults living with dementia remain ambiguous and warrant further guidance. On the basis of this QES, VR provides a means of facilitating sociability outcomes despite not being designed for this specific focus. Consequently, the authors suggest future exploration of Social VR for older adults living with dementia to facilitate social connectedness through multiuser VR spaces.

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Authors' Contributions

AF, DC, CH, and DH conceived and designed the review. AF performed the literature searches. AF and DH completed screening, data extraction, quality appraisal, and assessment of confidence in the research findings. DC and CH provided supervisory support and methodological consultation throughout the review process. AF, DH, CH, DC, MB, AB, and SR contributed to the conceptualization of the manuscript and reviewed multiple drafts. DC and CH contributed equally to the review as last authors.

Conflicts of Interest

None declared.

Multimedia Appendix 1
Search strategy.
[DOCX File , 14 KB - games_v10i4e37228_app1.docx]

Multimedia Appendix 2
Screening log.
[DOCX File , 19 KB - games_v10i4e37228_app2.docx]

Multimedia Appendix 3
Inclusion and exclusion criteria.
[DOCX File , 16 KB - games_v10i4e37228_app3.docx]

Multimedia Appendix 4
Characteristics of included studies table.
[DOCX File , 31 KB - games_v10i4e37228_app4.docx]

Multimedia Appendix 5
Methodological limitations.
[DOCX File , 18 KB - games_v10i4e37228_app5.docx]

Multimedia Appendix 6
Summary of qualitative findings and confidence rating.
[DOCX File , 16 KB - games_v10i4e37228_app6.docx]

Multimedia Appendix 7
Confidence in the evidence from reviews of qualitative research (GRADE-CERQual) full evidence profile.
[DOCX File , 55 KB - games_v10i4e37228_app7.docx]

Multimedia Appendix 8
Supporting quotations.
[DOCX File , 18 KB - games_v10i4e37228_app8.docx]

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Abbreviations

GRADE-CERQual: confidence in the evidence from reviews of qualitative research
HCI: human-computer interaction
HMD: head-mounted display
MeSH: medical subject headings
OT: occupational therapy
PRISMA: Preferred Reporting Item for Systematic Reviews and Meta-Analyses
QES: qualitative evidence synthesis
RACF: Residential Aged Care Facility
RETREAT: Review question-Epistemology-Time or Timescale-Resources-Expertise-Audience and purpose-Type of Data
VE: virtual environment
VR: virtual reality

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